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# Examination of Automatic Data Reduction Methods for Particle Field Holograms

Spectron Development Labs, Inc, Costa Mesa, CA

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Holographic recording techniques provide one of the most powerful particle field diagnostic tools in existence. A hologram can provide a frozen three-dimensional image of a particle field through which detailed microscopic examination of individual particles is possibe. Frequently, a particle field may contain many thousands of particles, and it becomes impractical for the human operator to glean all the data of interest from such a hologram. For holography to reach its full potential in particle diagnostics, a three-dimensional image analyzer is required.

The purpose of this study was to examine the feasibility of using existing electro-optic image analyzers to automatically analyze three-dimensional image fields and to determine what modifications of existing equipment would be required to construct such a system.

Sample holograms as well as holograms produced in an actual field holo-camera were used to make the evaluations experimentally, and well-refined analytical descriptions of holographic images were used to add to the understanding of system requirements. The study established that existing image analyzers are capable within useful practical limits of locating particle images in three-dimensions and measuring size and shape factors of the particle. A plan for integrating such equipment to produce a fully automated data reduction system is presented.

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January 1979

# EXAMINATION OF AUTOMATIC DATA REDUCTION METHODS FOR PARTICLE FIELD HOLOGRAMS

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## ABSTRACT

Holographic recording techniques provide one of the most powerful particle field diagnostic tools in existence. A hologram can provide a frozen three-dimensional image of a particle field through which detailed microscopic examination of individual particles is possible. Frequently, a particle field may contain many thousands of particles, and it becomes impractical for the human operator to glean all the data of interest from such a hologram. For holography to reach its full potential in particle diagnostics, a three-dimensional image analyzer is required.

The purpose of this study was to examine the feasibility of using existing electro-optic image analyzers to automatically analyze three-dimensional image fields and to determine what modifications of existing equipment would be required to construct such a system.

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# SECTION 1

# INTRODUCTION

## BACKGROUND

Holography has provided a new and powerful technique in the study of particle fields. Holography can be used to freeze the three-dimensional image of a particle field which covers a relatively large volume. The hologram is then used to reconstruct this three-dimensional image at which time the image can be probed in great detail microscopically to study individual particles and their properties, including size, shape, and velocity. The method can be used to extend the depth of field of the study of a dynamic particle volume by three or four orders of magnitude over that available to photography or microscopy.

Although particle field holography has now been used for a number of years in applications where no other method will work and has become an accepted diagnostic tool, the method still suffers a number of serious limitations which limit its use or make its use impractical for some studies. Holograms contain vast amounts of information. Extracting that information can be an extremely tedious and time-consuming task. If that task can be performed automatically by machines, then holography could be attractive in many more types of studies than it is now.

The field of electro-optics has produced a number of two-dimensional image analyzing systems. For example, an image can be inserted into such a system by way of a photograph of a negative and the system almost instantaneously can convert this image information into a computer-compatible format such that data processing is very quick. Holographic images are three-dimensional and, therefore, an image analyzing system must have the capability of determining another important piece of information. More specifically, the system must be able to define which plane in the three-dimensional image is in focus at any given time and is currently undergoing analysis. All the information taken from that given plane must be so designated to have arisen from that particular plane.

During this study we examined the capabilities of existing image analyzing equipment to determine if such equipment was easily adaptable to provide this requirement which was necessary for automated holographic data analysis. We paid particular attention to a system produced by the Cambridge Instrument Company Incorporated (IMANCO System) since the EPA currently has one of these systems. We found that this system already has the necessary programming capability to determine when an image is in focus if the image is of sufficiently high quality. Therefore, our next step was to determine a quality

factor which could be used to describe a hologram capable of producing such an image. The question, therefore, became not can three-dimensional images be automatically analyzed, but rather how good must the three-dimensional image be in order for it to be analyzed by currently existing image analyzers. More specifically, how good must the hologram be which produced this image. We then produced a number of holograms of both calibrated particle fields and typical particle fields, both in the laboratory and in an SDL field-portable holocamera, to determine how practical such a complete system would be. We found that when the proper conditions were met by correct field holocamera design, it is entirely feasible to produce useful holograms in the field which can be analyzed automatically by computer. It is our belief that such a system could be extremely useful in a vast number of requirements of the Environmental Protection Agency.

A specific limitation of the system which may prevent its widespread use by a large number of groups at this time is the expense of the overall system. However, since the EPA already has the image analyzing computer, this should not be a factor for the use by the EPA.

SDL has constructed and used a wide variety of field-portable holocamera systems under almost every conceivable naturally occurring environmental condition. We have found that almost without fail, such a holocamera can be tailored to meet the problems of any naturally occurring environment. Such systems have been used in aircraft, in field trailer systems, and in weather observatories, in conditions ranging from 40°F below zero to over 120°F, under extreme weather conditions. These systems are capable of producing holograms of quality sufficient to be reduced automatically. Such systems will be described in this report.

## PURPOSE OF THE REPORT

This is a final report covering a relatively small effort to determine the feasibility of practical use of automated image analysis systems in reducing holographic particle field data. In Section 3 we provide a brief explanation of particle field holography and its variations after which the discussion is extended to the properties of reconstructed images. This provides the necessary background for the search for an automated holographic data reduction technique. In Section 4 we describe an image analyzing computer system which was chosen for further experimental work and describe experiments which were carried out on actual reconstructed images from a variety of holograms of particle fields. In Section 5 we describe a typical field-portable holocamera which can produce holograms of the quality necessary for use in an automatic data reduction system. In Section 6 a more detailed layout of the holocamera recording and data reduction system is presented.

## SECTION 2

## CONCLUSIONS AND RECOMMENDATIONS

During the course of this study, we have produced a wide variety of holograms. These holograms range in quality from the ultimate or ideal quality that can be produced in a laboratory over a very limited known particle field to the quality that arises from an operational portable field holocamera which is used in routine data collection in studies ranging from weather to explosion diagnostics.

Taking holograms produced for this study, we concluded that existing optical image analysis equipment was sufficient to reduce images reconstructed from holograms produced in a good field holocamera. Therefore, we have concluded that the equipment necessary to automatically reduce holographic data exists in various components and needs only to be assembled and integrated for application to holography. We have shown that the TV resolution is sufficient for a wide range of interests of holographic images, the system is capable of rejecting common types of noise which normally would make data reduction difficult, the system is capable of eliminating common speckle type of noise, the system is capable of sizing particles of interest, and the system is capable of determining when a particle is in focus.

The remaining task is to design such an integrated system in detail so that the remaining components can be procured and assembled into a working unit. At this stage the computer software for that specific system must be developed. The principal item to be procured in this development is the computer-driven x,y,z traverse onto which the hologram is mounted. This traverse could be driven by a number of different computers. In fact, the Hewlett-Packard desk top calculator which we used during this study could perform that task, although it would be limited in speed. A more preferable system would be a minicomputer which would allow the data handling as well as the traversing capability to be greatly enhanced. We would recommend the EPA make plans to assemble such a system for use with their existing Quantimet 720 image analyzer such that an automated holographic data analyzing system would be available for use in particle field studies.

## SECTION 3

## REVIEW OF PARTICLE FIELD HOLOGRAPHY

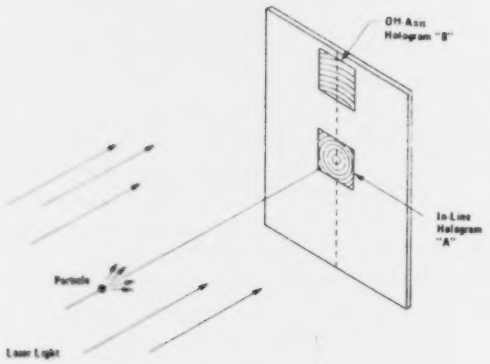
### HOW HOLOGRAPHY OFFERS ADVANTAGES

The purpose of this section is to review the current state-of-the-art and to present examples of applications of holography in the study of particle fields.

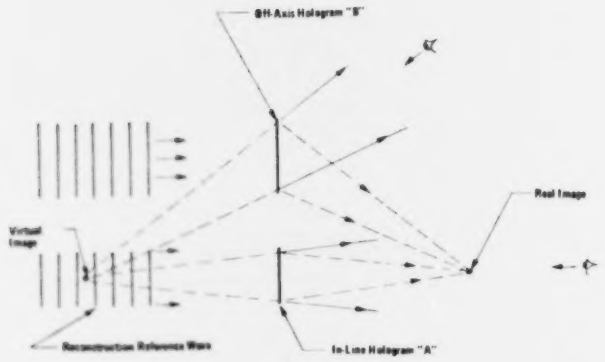
An optical hologram is a special type of recording of a light wave which stores all the information necessary to reconstruct an essentially identical light wave at a later time. The three-dimensional image of a field is viewed through a hologram as if the hologram were a window behind which the actual field was frozen in time. It is a simple matter to convert this virtual image (which lies behind the hologram) to a real spatial image (which lies on the viewer's side of the hologram). A hologram is formed by mixing coherent light scattered from the field of interest (object beam) with a reproducible mutually coherent (reference) beam, Figure 1(a), and recording the intensity of the sum on a photographic emulsion or other recording medium (there are many types). When the hologram is once again illuminated by the reference beam, Figure 1(b), the hologram, acting as a special type of diffraction grating, changes the reference beam into several components, one of which is nearly identical in information content to the original object beam. The reconstructed beam is never exactly identical to the original beam simply because the recording and reconstruction processes are not ideal. Optical noise and aberrations cause resolution limits on the process which are thoroughly discussed, for example, in Reference 1.

When particles can be trapped on slides, replicated in plastic, or frozen in space, conventional methods of viewing and photographing are usually satisfactory, if not superior. When they cannot be trapped, more unconventional methods are necessary. The need for in situ characterization of particles in all fields of science has spurred the development of many techniques based on light scattering and extinction laws, nucleation phenomena, shadow detection, and measurement of other properties which can be related back to particle size, number, and type. In many cases large numbers of particles are involved and statistical properties of the entire sample are of more interest than individual particles. In such cases the detailed examination of individual particles may not be required. Holography is particularly powerful when it is desired to examine individual particles in a distribution.

All optical imaging measurements, holography included, are resolution limited by the laws of diffraction. The precise limit of resolution for any optical system depends upon a somewhat arbitrary definition of resolution,




(a) In-line and off-axis hologram of a point object.




(b) Forming the image with the hologram.

Figure 1. Holography of a point source.

however, the same parameters are involved and the resulting numbers differ only by small multiplicative factors. The resolution of any optical system is directly proportional to the size of the angular cone of light (emerging from the resolution point) which is faithfully conveyed or recorded by the optical system. Resolution is also proportional to wavelength of light being used. The diffraction limited resolution limit predicted by the familiar Rayleigh criteria is approximately $1.3\lambda S/D = R$ where the D is the diameter of the usable cone of light at the optical element and S is the distance of the point from the element. For a particular object/image pair in an imaging system, there is a certain variation in S over which changes in the image are not detectable. This so-called depth-of-field is a function of resolution given approximately by $\delta = R^2/2\lambda$. So an imaging system with high resolution is a short field depth system. All direct imaging particle field analyzers are, therefore, bound to rather small sample volumes. It is important to recognize that the quantity D is the diameter of the useful cone of light and is not necessarily the physical diameter of a lens or hologram. One extremely important practical resolution limiting parameter in any system is optical noise. The way it adds to the actual information and the signal-to-noise ratio play an important role in specifying the true value of D.

Holograms in particle field analysis simply provide an intermediate storage step which optically freezes the three-dimensional field of particles. Holograms extend the depth-of-field capability for analysis but not infinitely as is often believed. The hologram must record faithfully the proper cone of light before a particle can be resolved in the reconstructed image. This leads to the result that the higher the resolution required, the smaller the volume over which the hologram is useful. Holography currently records a useful volume depth which is three to four orders of magnitude greater than photography. The size range can vary from submicron to very large particles. Applications include such areas as holomicroscopy in biology, cloud physics, physics of explosions, nozzle and spray analysis, fuel injection and burning processes, bubble tracking, nucleation phenomena, particle tracing in aerodynamics, pollution, and two-phase flows.

## CHOOSING A HOLOGRAPHY SYSTEM

In examining a particle field by holography the investigator is immediately faced with a selection from a large number of system types. If the field is dynamic, the laser source must be a short-pulsed, high-powered system. At the present time this essentially limits the choice to either a Q-switched ruby (0.694 microns wavelength) or a frequency doubled YAG system (0.530 microns wavelength). Although pulsed or mode locked gas lasers are suitable for some applications, their use is extremely limited because of lack of power. A choice of type of illumination, direct or diffuse, must then be made. It may be desired to record all of the light passing through the field or to limit the recording to light scattered by particles in the field (see Figure 1(a), off-axis case). In-line or off-axis holography must be chosen. Finally, the decision must be made to make the hologram of the field directly or to image the field first. Some of these choices are illustrated here.

An in-line hologram is made by passing coherent light through a volume of particles and recording the resulting wavefront (Figure 2). Part of the light is diffracted by the particles and the remainder passes through the field unscattered. The unscattered (reference) light interferes with the scattered (object) light and is recorded on a photographic medium. An off-axis hologram is formed by introducing a reference wave which is separate from the light passing through the object field onto the recording (Figure 3). The laser beam is split initially in two. One portion illuminates the object field, while the other serves as the reference beam. Many geometries are suitable for off-axis holography. The object field can be illuminated directly with the laser beam or with laser light that has been diffused by a frosted glass or similar diffusing medium.

The object wave in both in-line and off-axis cases is reconstructed by illuminating the developed recording with the reference wave. Equation (1) predicts the position of the reconstructed image as a function of the wavelength, radius of curvature, and position of the reference wave. (Figure 4 illustrates the geometry for Equation (1).)

$$z_i = \left( \frac{1}{z_p} + \frac{\lambda_2}{\lambda_1 z_r} \mp \frac{\lambda_2}{\lambda_1 z_o} \right)^{-1}$$

$$x_i = \mp \frac{\lambda_2}{\lambda_1} \frac{z_i}{z_o} x_o \pm \frac{\lambda_2}{\lambda_1} \frac{z_i}{z_r} x_r + \frac{z_i}{z_p} x_p \qquad (1)$$

$$y_i = \mp \frac{\lambda_2}{\lambda_1} \frac{z_i}{z_o} y_o \pm \frac{\lambda_2}{\lambda_1} \frac{z_i}{z_r} y_r + \frac{z_i}{z_p} y_p .$$

These equations result from a first order analysis of thin holograms and are not accurate when large changes in wavelength or reference wave curvature are encountered. A more general analysis is treated in Reference 1.

There are no hard, fast rules for choosing one specific type of system for a given application. In-line holography is the simplest type of holography and perhaps should always be considered first in particle field studies. However, there are many cases in which off-axis holography is applicable and in-line holography is not. Such cases exist when the particle number density or their total cross section is very large or when the object field significantly modulates the phase of the electromagnetic radiation. A sufficient amount of light (typically about 80 percent) must pass through the field without modulation to serve as a reference wave to produce a good in-line hologram.

When a field is illuminated by diffuse illumination, the resulting reconstructed image is easier to view with the naked eye. Associated with diffuse illumination are speckle patterns which cause problems in high resolution viewing. In any viewing plane the background of illumination is not

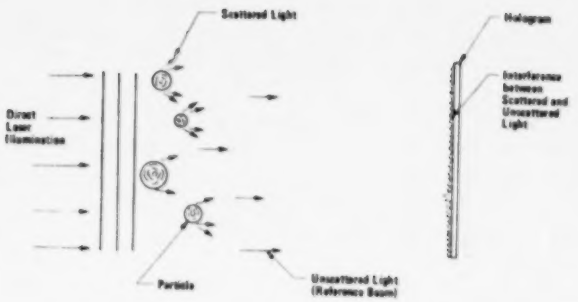



Figure 2. In-line hologram of a particle field.

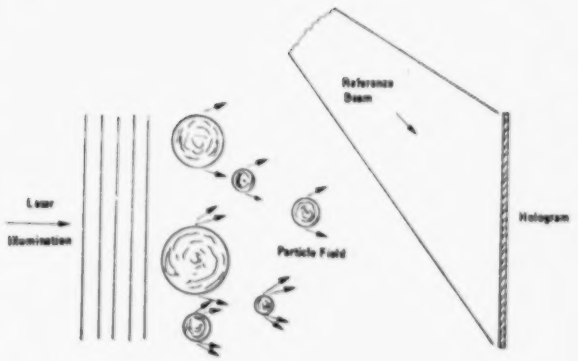
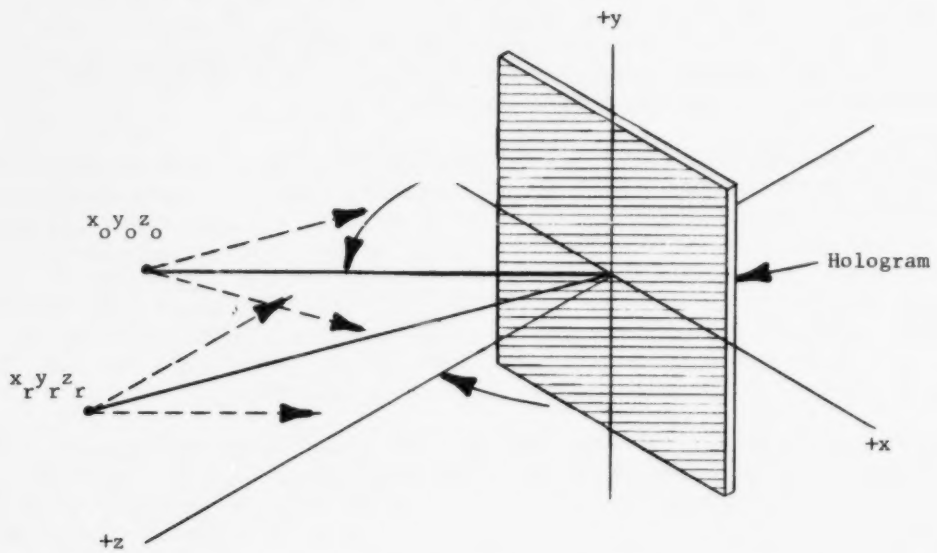
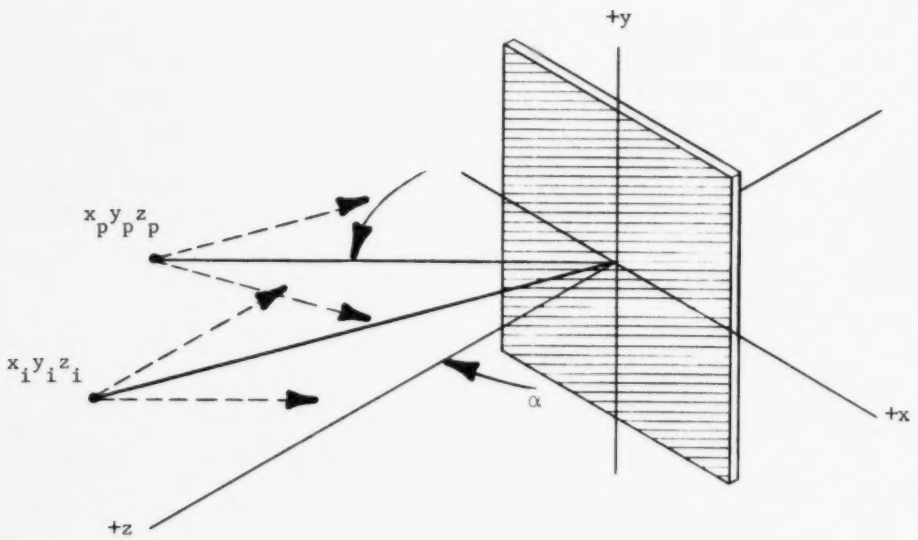



Figure 3. Off-axis hologram of a particle field.




Producing the Hologram of a Point

sub o ~ object wave
sub r ~ reference wave
sub p ~ reconstructing wave
sub i ~ reconstructed wave




Reconstructing the Point Image

Figure 4. Geometry for Equation (1).

uniform; it is formed by speckle points of varying size and separation. The mean speckle separation is about twice the resolution of the original recording system. Therefore, the resolution limit of the holography system must be five to ten times smaller than the smallest particle to be observed so that particles can be distinguished from speckle.

To see the smallest particles in the reconstructed image requires a total system of low noise. Even those particles which are much smaller than the system resolution limits can be seen as points of light whose brightness can be associated with size. The task is to separate these points from the optical noise. One of the most powerful methods for seeing particles in the submicron and micron size range is the holographic recording of scattered light only, against a dark background. The particle field is illuminated by a pencil or sheet of light and the hologram of scattered light is made at some angle away from the axis of the illuminating beam.

The hologram itself is often the poorest quality optical element in the system because the emulsion adds phase and amplitude noise to the recording and reconstruction process. This element can be improved by such techniques as liquid gating and special photographic procedures[3]. Such methods are tedious and are avoided in most applications.

Holograms possess most of the properties of lenses. In practice, however, lenses are better imaging elements than holograms and are combined with them to attain higher resolution and larger working distance. When the field of interest must be located at a relatively large distance from the nearest optical element, lenses or mirrors are normally used to image the field closer to the hologram to maintain high resolution. A lens hologram combination can be used in such a way to completely correct aberrations in the lens during reconstruction. Although high magnification is possible in principle in holography without lenses, the most successful applications have resulted from combinations of conventional with holographic magnification. A well-designed holography system will normally produce ultimate image quality and resolution which is slightly poorer than a conventional optical system which is focused on an object plane, but it will do this over a volume in a single recording. A detailed review of particle field holography is given in References 2 and 3.

## SECTION 4

## AUTOMATIC PROCESSING OF PARTICLE FIELD HOLOGRAMS

### INTRODUCTION

There are two basic limitations of holography systems for particle field studies which are suffered in almost all current applications. First, data recording rates are too slow. One sample volume, typically on the order of a liter, can be recorded every few seconds. This rate is too slow to provide ample statistics in many cases. Second, data reductions from holograms require tedious, time consuming procedures which make it difficult to reduce even the quantities of data generated by existing systems.

The technology for increasing data recording rate is here; however, it would make little sense to increase the data recording rate without first insuring that methods to rapidly reduce the data are forthcoming. Therefore, it is reasonable to first remove the holographic data reduction bottleneck and define the quality of data required for rapid data reduction. This will tell us how good the recordings must be and how many can practically be reduced.

Two different kinds of holography data must be considered, depending upon the type of light which is used to illuminate the particle field. The field may be illuminated with diffuse light or with direct laser light.

To illuminate a particle field diffusely, the laser beam is expanded onto a frosted glass or other diffuser which is placed behind the sample volume. A reference beam is carried around the sample volume where it is mixed with the light from the sample volume onto the hologram. The hologram looks like a uniformly exposed piece of film, appearing to contain no information at all. The reconstructed image appears to contain dark, shadow images against a diffuse light background. As previously explained, the problem with this method occurs in high resolution studies.

Diffuse illumination has some advantages. The reconstructed image can easily be viewed with the naked eye, with the particle field appearing against a bright background. A particle is illuminated from a relatively wide angle of directions, and accordingly can be viewed over that wide angle. This provides two benefits. First, since forward scattered light is greatest, it provides for a wider angle over which forward scattered light can be recorded. This makes a more uniform recording which would exhibit higher resolution, except for the effects of speckle. Second, the particle image, being backed by a diffuse field, has essentially no out-of-focus shadow. The out-of-focus image blends into the background in such a way that it cannot be distinguished

from the background when defocused by typically 100 particle diameters (depending upon the system). This feature provides a simply defined focusing property of the image.

Direct light holograms are produced when the particle field is illuminated by light directly from the laser with lenses being used to expand the beam large enough to fill the sample volume. The reference beam is either (1) the unscattered beam passing through the sample volume or (2) a separate beam introduced onto the hologram by another path around the sample volume. In either case, the hologram appears as a more or less uniformly exposed piece of film with diffraction patterns and fringes superimposed. For each particle in the volume from the laser to the film there is a diffraction pattern (a coherent shadow) which is a set of more or less circular concentric rings. When reilluminated by the laser, each of these diffraction patterns diffracts light into a particle image in its original position in 3-D space.

When passing through the focused plane of an image, the diffraction pattern collapses into a sharp high contrast image which is bright against dark for in-line holography and dark against bright for off-axis holography. After passing through the focused plane, the defocused image (shadow or diffraction pattern) expands in size and loses its characteristic shape ultimately appearing as a somewhat circular set of diffraction rings bearing no resemblance to the original particle.

## EXISTING DATA REDUCTION TECHNIQUE

The reconstructed 3-D image of the sample volume is scanned either by moving the hologram and passing the image over a viewing device or by moving the viewing device through the sample volume image. The simplest type of viewing device is a microscope which the viewer scans by hand. This technique is the one we use in the field for hologram quality evaluation. However, viewing large numbers of reconstructed holographic images through a microscope by eye is extremely tiring. In most laboratories, extensive data reduction is accomplished by converting the coherent reconstructed image (normally a red image from a HeNe laser) to an incoherent black and white image by projecting it into a closed circuit TV system. Final viewing of the image is done on the TV monitor. When focused on the TV monitor, the image may be studied, sized, photographed, or sketched.

Consider a typical particle field hologram from our field portable holography system. The sample volume has a cross sectional area of about 25 $cm^2$ and a length of 15 cm. A 100 micron particle should appear about 1 cm across on the TV monitor for comfortable viewing; that is, a magnification of about 100. The TV magnifies electronically by 25, the remainder is achieved optically upon reconstruction either with lenses or holographically (see Equation (1)). The actual cross sectional area viewable on the TV screen represents an actual area of about .05 $cm^2$ under these conditions. Therefore, 500 in-depth scans are required to analyze the entire hologram. This can take an operator an entire day, depending upon what data he is collecting.

Considering the fact that in a single day's operation of the system hundreds of holograms can be recorded, the data handling problem becomes

cumbersome. Normally the data output comprises photographs, number counts, size distributions and, in some cases, spatial and velocity distributions.

## THE TASK OF AUTOMATING DATA REDUCTION

Consider the task performed by the human operator. In general he must scan through the 3-D field while watching image characteristics. In the case of direct light holograms, he can tell directly from the hologram what the xy positions of particles will be by locating diffraction patterns. Some of these particles are contamination on windows and in the optical train. If two holograms made in the same system at different times are placed side by side, he can mentally subtract one from the other leaving only diffraction patterns which are not common to the two. These represent the particles in the sample volume. He could immediately count the number of particles (or determine velocities) directly from the hologram without reconstruction. To see the particle he must locate the focused position, z, during reconstruction. The human operator uses the following characteristics to decide upon the focused position:

(1) The diffraction pattern converges to form an image;
(2) The light distribution becomes more intense in the image;
(3) Image edges become defined;
(4) He sees an expected shape or combination of shapes emerge;
(5) Optical noise is mentally rejected because it has different characteristics than the image.

Every criteria used by a human operator can be stated mathematically and can be sensed optically and/or electronically. Therefore, in principle, the reduction of holographic data can be done by machine. In fact, for almost every criteria there exist several machine processes which can, in principle, perform the human task. Determining factors in the rapidity with which a human operator can function in holographic data reduction are memory and response to learned characteristics. Both factors are poor during the first hour or so of a data reduction session. They peak for a period of only an hour or so and then decline as the operator becomes tired or succumbs to monotony, resulting in variable judgment and poor efficiency. A well-programmed machine would excel in this respect because it could exercise the best knowledge of a skilled operator with more speed, consistency and endurance.

A higher quality hologram requires less skill and judgment in data reduction and, therefore, can be automatically reduced by a less complicated machine. As the quality of a hologram get poorer, so does the practicality of devising an automatic data reduction machine. (In fact, a certain point is reached whereupon the required level of expertise of a human operator increases.) One of the tasks in automatic data reduction is to determine practical machine limitations for performing the above tasks so that a minimum quality hologram can be specified.

During this program, we examined a number of possible methods to accelerate data reduction. The most promising immediate approach was the extension of existing two-dimensional image analysis techniques. We performed experiments with the IMANCO "Quantimet" image analyzer located at the

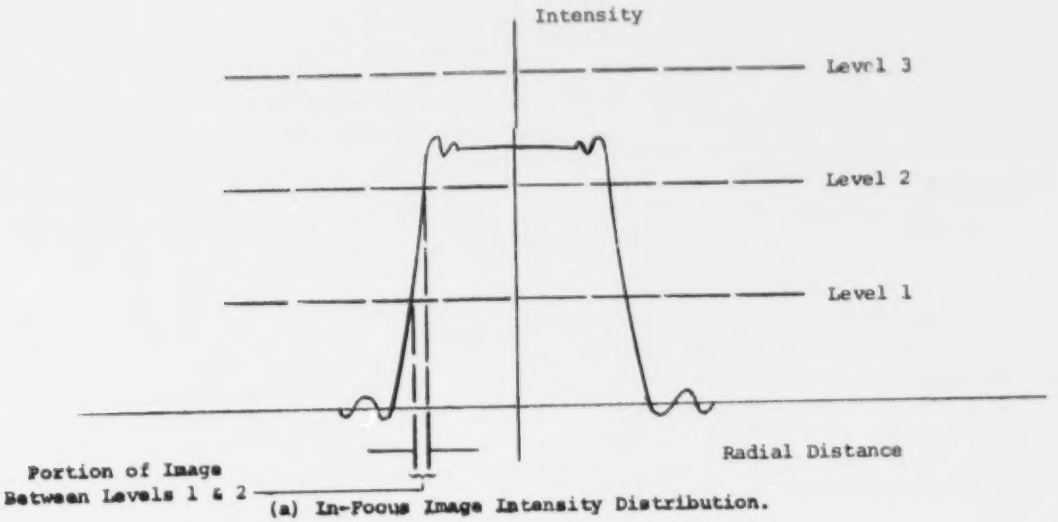
Cambridge IMANCO Instrument Company, Mountain View, California, office. The results are described in the following subsection.

## EVALUATION OF THE QUANTIMET SYSTEM FOR HOLOGRAPHIC IMAGE ANALYSIS

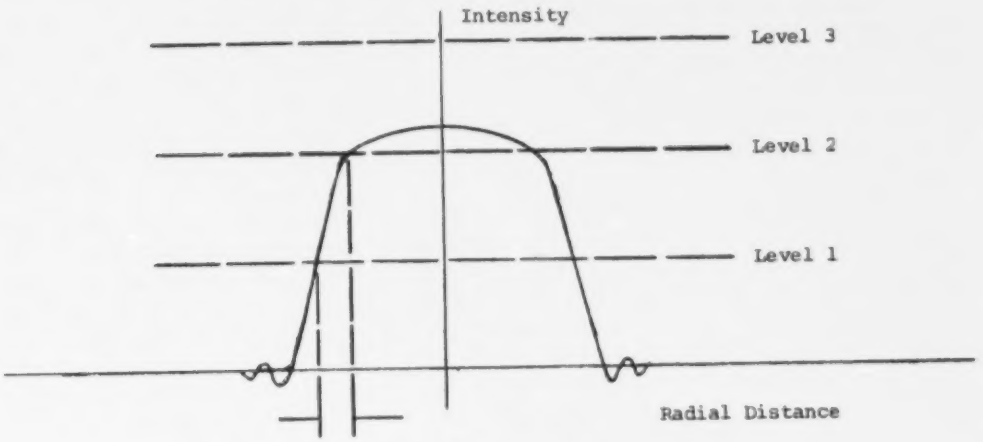
### Existing Work

Shortly after we had begun this investigation for the Environmental Protection Agency, a group of scientists with whom we had been in touch working for the Meteorological Office in the United Kingdom had independently chosen the IMANCO system to apply to the data reduction of holograms produced in weather and in environmental studies. In Reference 4, they describe a series of experiments in which they analyzed holograms with this system. The information gained from those studies actually gave us a head start in the conduct of our own studies.

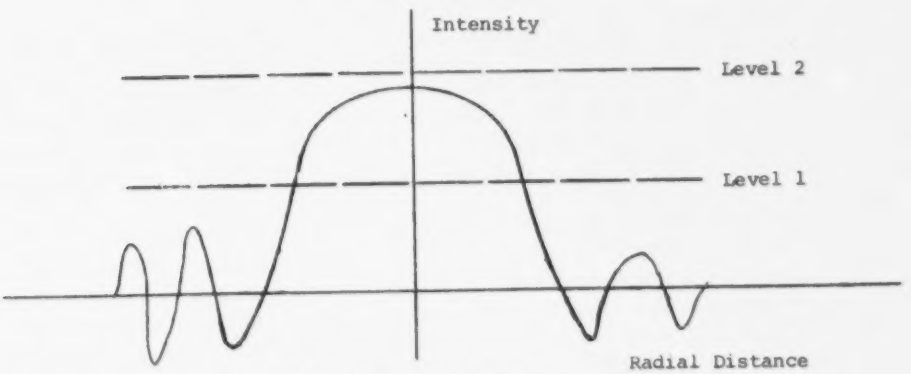
As previously described, the new problem involved in adapting the IMANCO system to holographic data reduction is to force this system to differentiate between particles which are in focus and out of focus, therefore, allowing a scan automatically of the third dimension. They showed, for example, that the existing IMANCO system was capable of performing the first three tasks which are outlined in the previous subsection. Consider, for example, the intensity distribution illustrated in Figure 5, which represents the cross-sectional intensity in the image of a particle as the particle passes through focus. Three levels were set into the IMANCO system to be used in image detection. Level 1 was set to be greater than the normal background noise. The IMANCO system, therefore, rejects any optical information below this level and does not display it on the TV monitor. Level 2 is set at some value higher than Level 1 but lower than the maximum intensity of an in-focus image of the particle. Level 3 was set to be higher than the intensity in the in-focus image of the particle. The determination of focus is made in the following way. When the image intensity exceeds Level 1 but not Level 2, it can be assumed that the particle is very badly out of focus and the system can continue scanning toward focus. When the intensity in the image increases to the point where it exceeds Level 2, it can be assumed that the image is approaching its in-focus condition and the scanning system can be slowed down. When the image nears its in-focus condition, the diameter of a particle as determined by the extent of the image going out to Level 2 should be approximately the same as that determined from Level 1. When the difference between the Level 1 diameter and the Level 2 diameter is at a minimum, the particle can be considered in focus, and the size determined by an average of the Level 1 and Level 2 diameter should be a good representation of the particle size. That information is recorded for that particular particle image. For some cases, an out-of-focus condition produces a higher intensity at the center of the particle image than away from the center, and these cases are rejected when the intensity in the image exceeds Level 3. The IMANCO system has the correct programming to allow the determination of minimum values such as that described here, and an output is available to drive interface equipment which would, in turn, control traverse systems. During the reported studies, a Hewlett-Packard 9830A was interfaced with the Quantimet to perform the task of driving the traverse which held the hologram under study.




(a) In-Focus Image Intensity Distribution.




(b) Out of Focus.




(c) Badly Out of Focus.

Figure 5. Intensity distribution in the intensity of an image.

## Experimental Investigation

To further evaluate the ability of the "Quantimet" system in hologram image analysis, we produced a wide variety of holograms. Three basic types of holograms were produced: (1) ideal laboratory quality under clean conditions (these were intended to represent the best case recordings), (2) holograms produced in the SDL field holocamera of controlled particle fields (controlled size and number density), and (3) holograms produced in the SDL field holocamera in a variety of natural environments.

Our intent was to determine what limitations would be exhibited by the "Quantimet" system. At first, we had planned to begin with the ideal best case holograms to provide a baseline. We decided very quickly that this would not be necessary. We observed that the Quantimet could, in fact, analyze almost all of the holograms we had produced. Some limitations will be illustrated. Therefore, we advanced to the holograms produced in the field tests, spending most of our time using the Quantimet to analyze actual field recorded holograms of particles.

The system used was the Cambridge IMANCO Quantimet 720 image analyzing computer interfaced with a Hewlett-Packard 9830A desk top calculating computer. All experiments with the Quantimet were conducted at the Cambridge Instrument Company's Mountain View office with the assistance of Mr. Brian Partridge, a Cambridge employee. The required holographic reconstruction equipment was transported to Mountain View for the experiments.

Figure 6(a)-(d) shows the experimental apparatus. The reconstructing laser was a Spectra-Physics Model 124 HeNe laser producing 15 mw of laser power at 633 nanometers wavelength. This beam was expanded and collimated after which it illuminated the hologram. All holograms were produced on 4x5 inch Agfa-Gavaert, Scientia emulsions. Both Agfa 10E75 and 8E75 plates were examined. Both in-line and off-axis recordings were produced. Only the in-line recordings were examined since a larger laser is required for off-axis reconstruction. An adjustable neutral density filter allowed us to adjust laser power at the hologram to optimize the interface between the reconstruction system and the TV camera.

The reconstructed image produced by these holograms is a one to one reconstruction of a 50 mm by 150 mm cylindrical volume which starts 10 mm from the hologram and extends to a distance 160 mm from the hologram. This image was magnified and relayed into the TV camera by a high quality copy lens, specially selected for this problem. As pointed out in Reference 4, cleanliness is an important factor with all optical elements in this system.

Figure 7 shows the face of the Quantimet monitor when a reconstructed three-dimensional image is presented to the associated TV camera. This is the "raw" image with none of the image processing capability engaged. Two different focus planes are illustrated. These figures can be used to explain the meaning of the various features in the figure. The inner frame is the active region for the system. The system can be described as a matrix of picture points 800 points wide by 625 points high. Therefore, it is convenient to use dimensions of picture points. In the top figure, a dimensioning

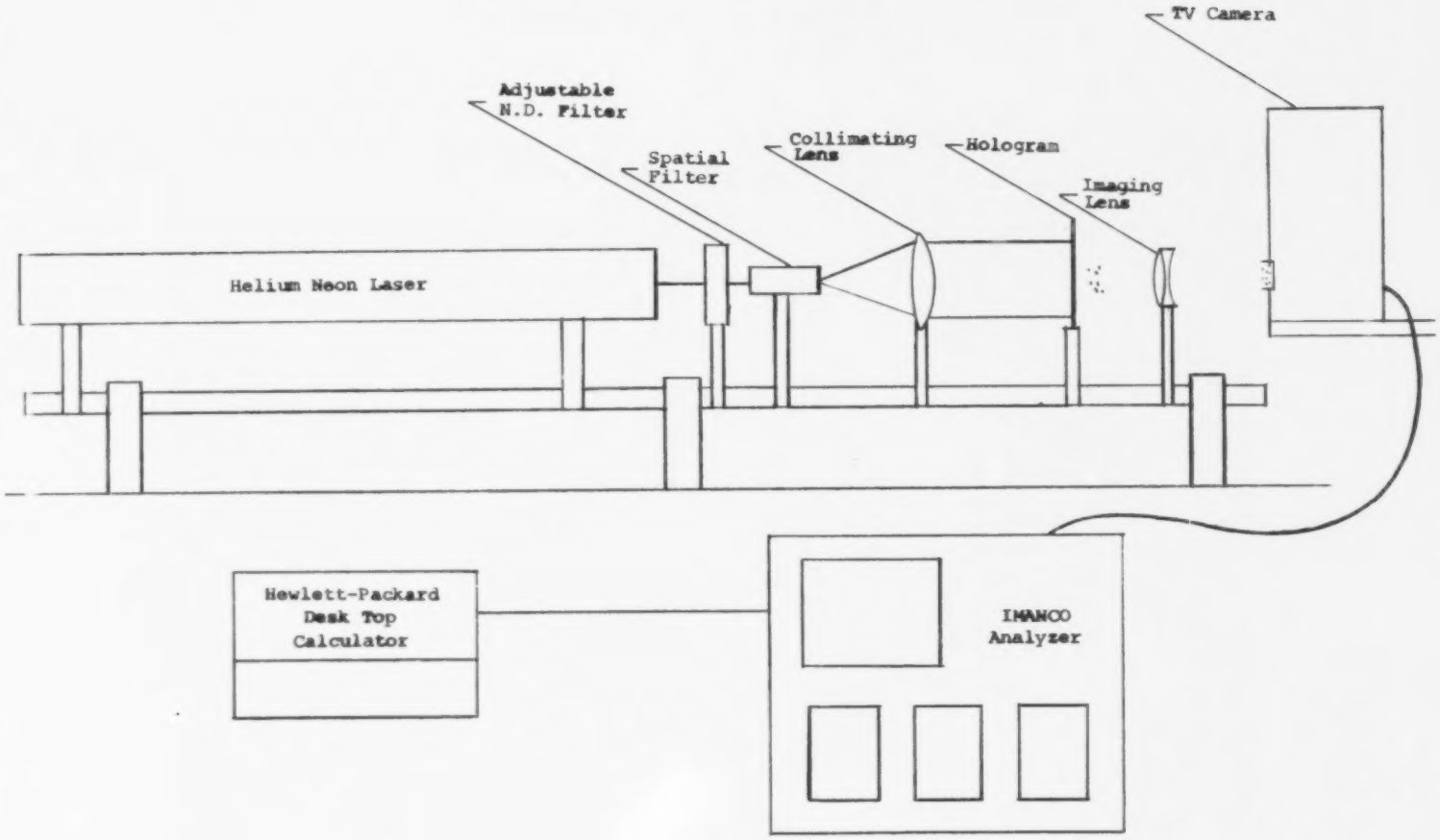



Figure 6(a). Hologram reconstruction setup.

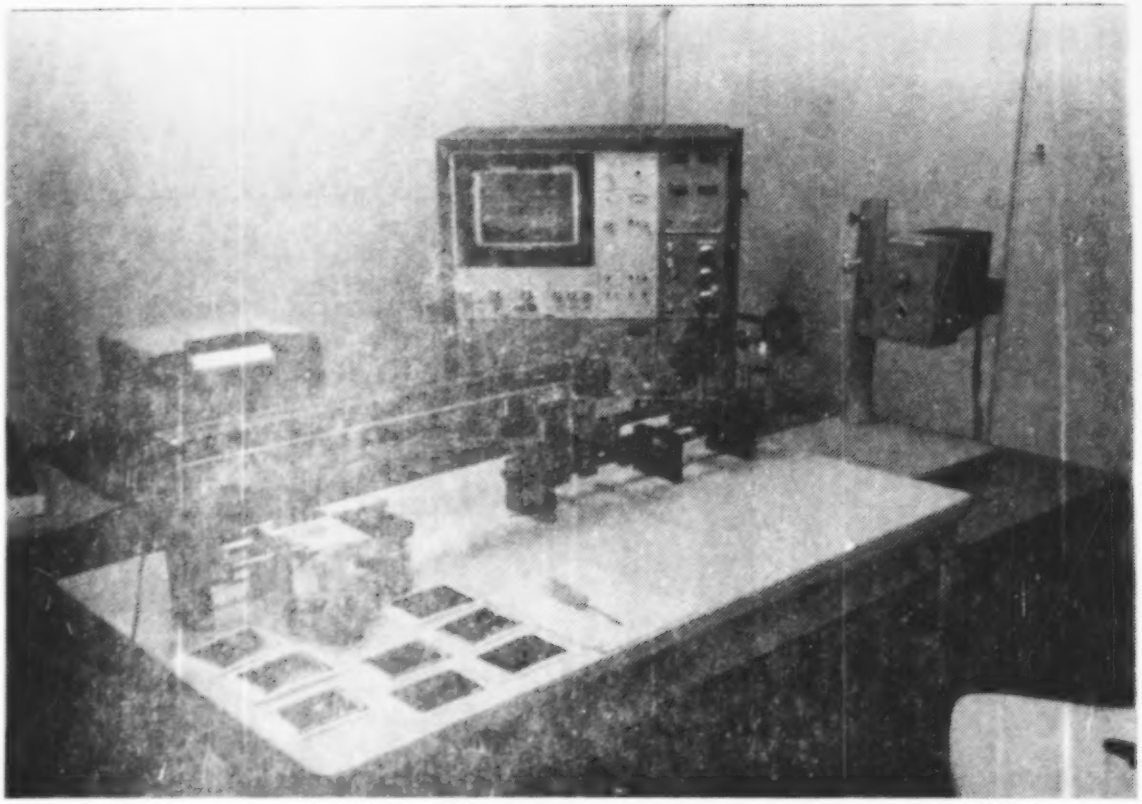


Figure 6(b). Experimental apparatus for machine data reduction of particle field holograms.

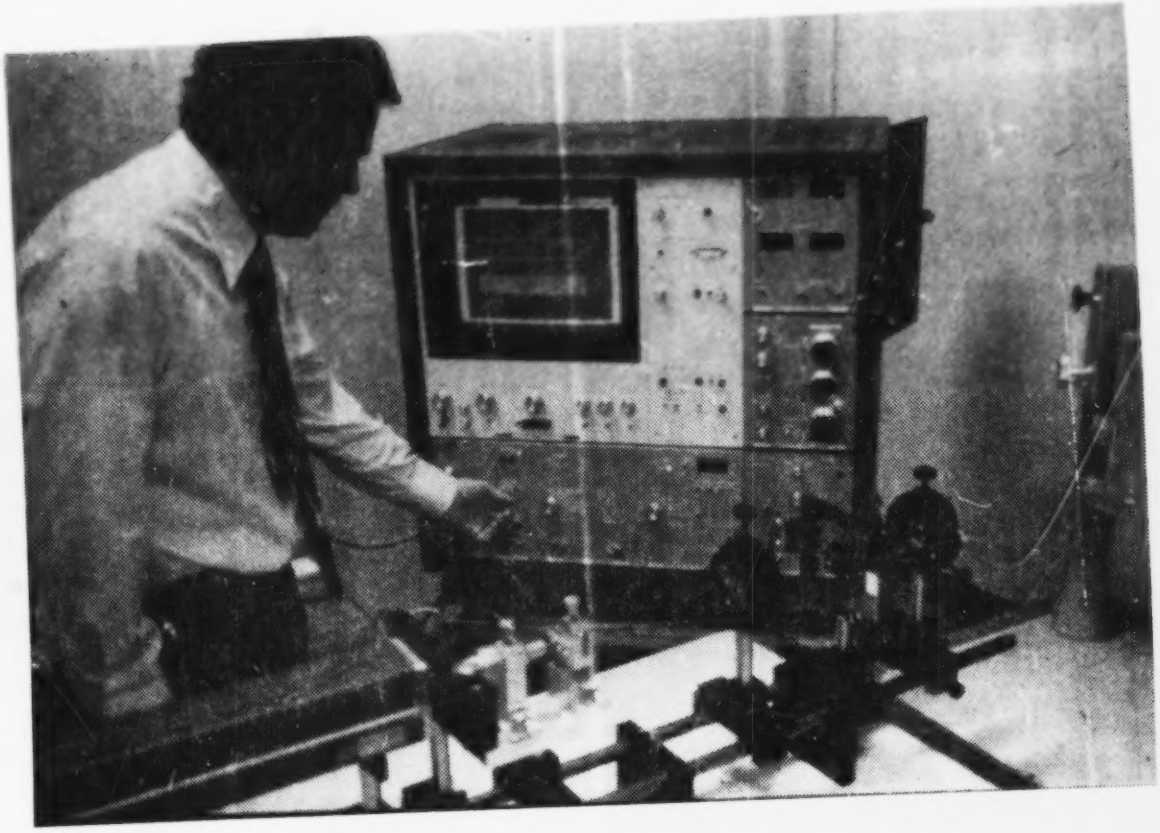
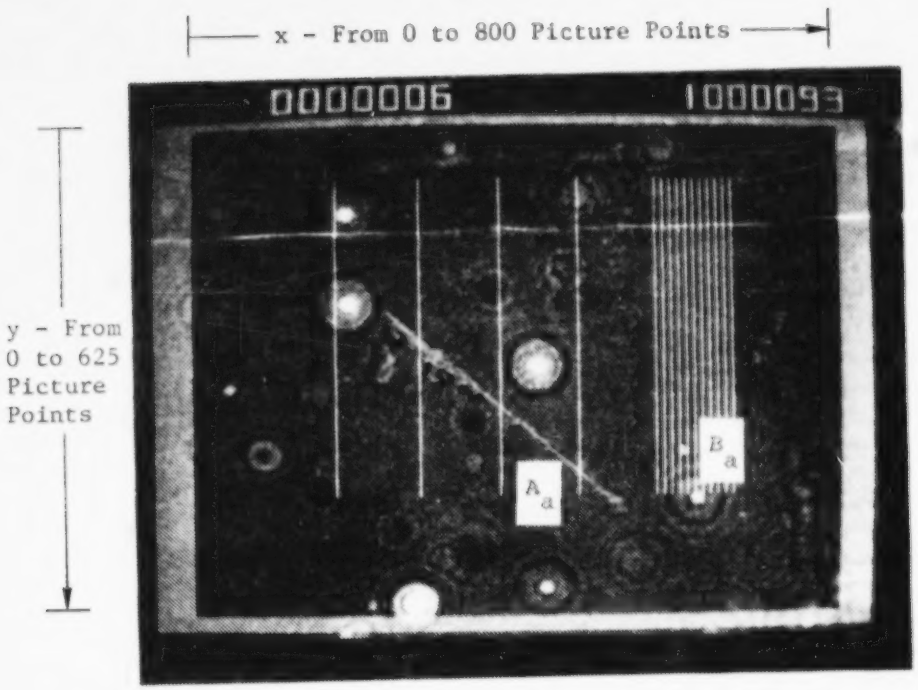


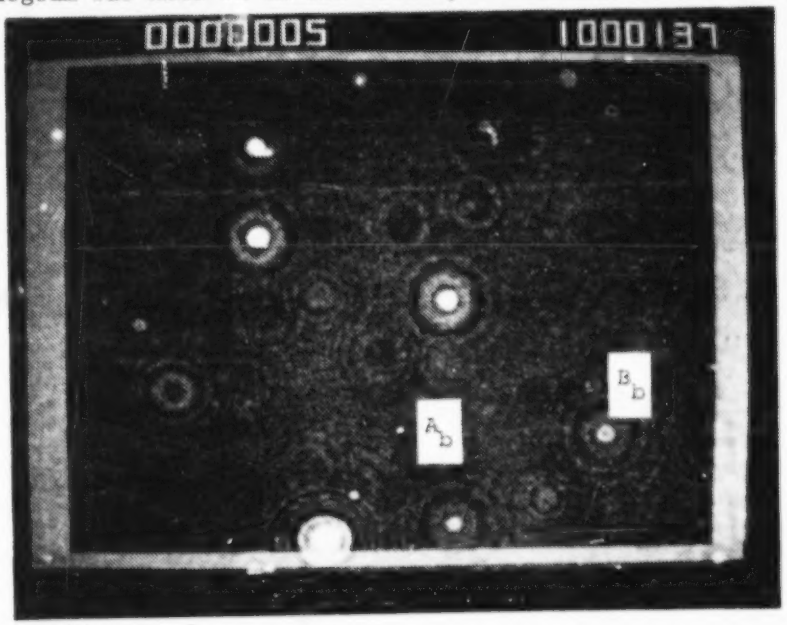
Figure 6(c). Adjusting the Quantimet system for a data run.

Figure 6(d). Recording hard copies from the monitor.




(a) z = 5 cm

NOTE: The hologram was made in an SDL field-portable holocamera in heavy fog.




(b) z = 7 cm

Figure 7. Two different planes of focus from a three-dimensional reconstructed image as displayed on the "Quantimet."

raster has been displayed on the monitor. The small elements are spaced by 10 picture points (p.p.). The number in the top left corner displays how many features (particles) were counted (six for this case). The top righthand number is the last dimension measured by the system.

We have identified certain regions of the image to illustrate its appearance as particles pass through focus. Region $A_a$ contains a diffraction pattern which is the out-of-focus coherent image of the particle shown in region $A_b$. Region $B_a$ contains an in-focus image which is out of focus in region $B_b$. These images are 20 micron diameter water droplets.

The program which we used determined the x and y positions of each feature, its area (A), perimeter (PERI), horizontal feret (FH), vertical feret (FV), 45° feret (FE), 135° feret (FW), horizontal projection (PH), vertical projection (PV), ratio of area to perimeter, and ratio of area to perimeter squared. Figure 8 illustrates the definition of each of these dimensions.

When the image is first presented to the TV camera, it appears as in Figure 7. The noisy background characteristic of holographic images is clearly evident. The first processing step is to set a threshold value of intensity below which all information is rejected. Figure 9 shows the images resulting from Figure 7 when this is done. This rejects entirely the small out-of-focus images whose intensity is spread over the Fraunhofer diffraction pattern. See, for example, regions $B_a$ and $A_b$. Larger particles are still detected over a rather large depth of field as can be expected. However, so long as size and not position is needed, the size of the particle image does not change drastically for a quite large depth of field, so it could be measured with reasonable accuracy in either figure (although it is truly in focus in only one thin planar region).

In Figure 9(a) six features were counted, while in Figure 9(b) only five were counted. A marker appears on the monitor beside each feature which is being analyzed. This will be useful to an operator allowing him to quickly evaluate the validity of what is being analyzed. A typical printout of data is shown in Table 1. (Dimensions are given in picture points, p.p.)

TABLE 1. PRINTOUT OF INFORMATION TAKEN FROM THE IMAGE ANALYSIS OF FIGURE 9(A)

| | X | Y | AREA | PERI | FH | FV | FE | FW | PH | PV | A/P | $A/P^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. | 235 | 163 | 101 | 39 | 11 | 12 | 16 | 14 | 12 | 12 | 2.590 | 0.066 |
| 2. | 241 | 273 | 154 | 47 | 15 | 14 | 18 | 18 | 14 | 15 | 3.277 | 0.070 |
| 3. | 473 | 355 | 194 | 56 | 18 | 17 | 18 | 20 | 17 | 18 | 3.464 | 0.062 |
| 4. | 678 | 526 | 79 | 34 | 10 | 10 | 14 | 14 | 10 | 10 | 2.324 | 0.068 |
| 5. | 482 | 643 | 34 | 23 | 8 | 8 | 8 | 12 | 8 | 8 | 1.478 | 0.064 |
| 6. | 321 | 670 | 485 | 82 | 26 | 24 | 30 | 30 | 24 | 26 | 5.915 | 0.072 |

The particles actually ranged in size from about 10 to 50 microns.

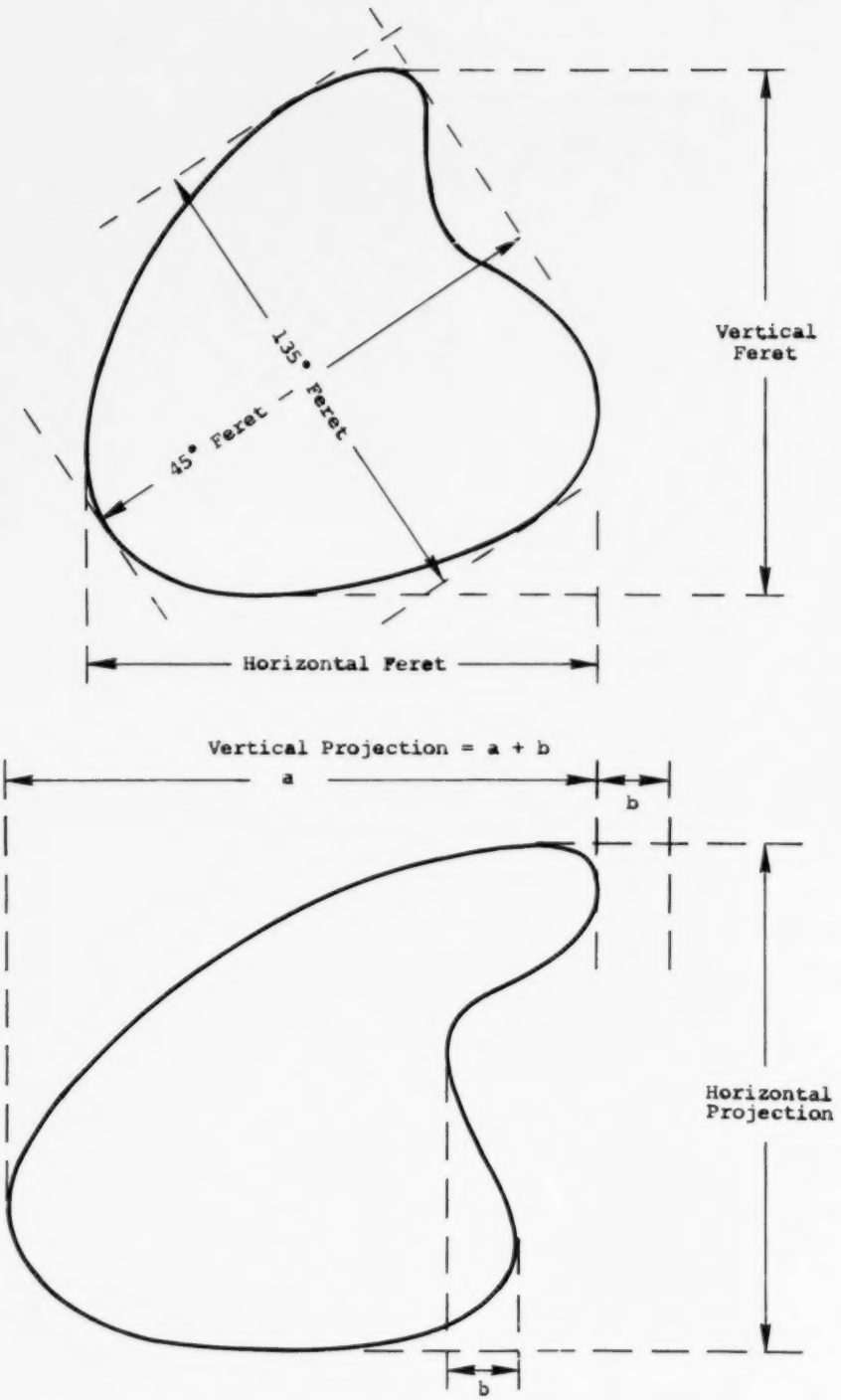
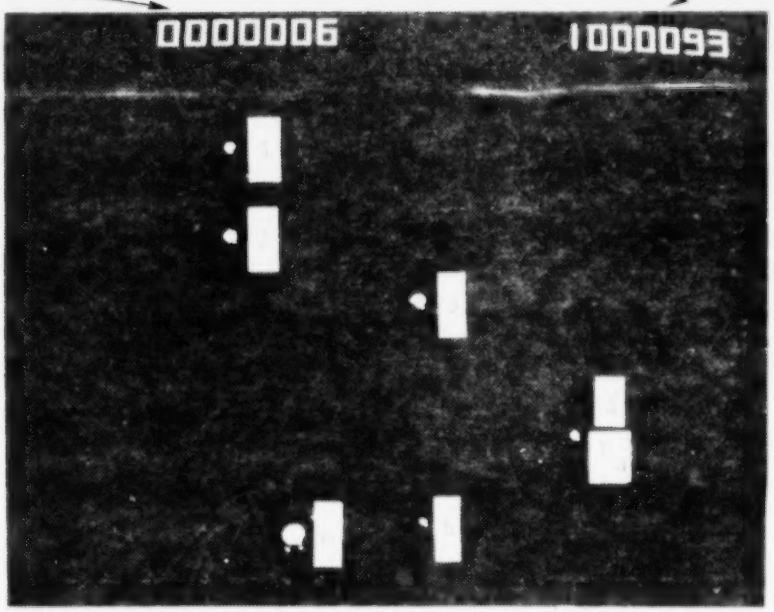


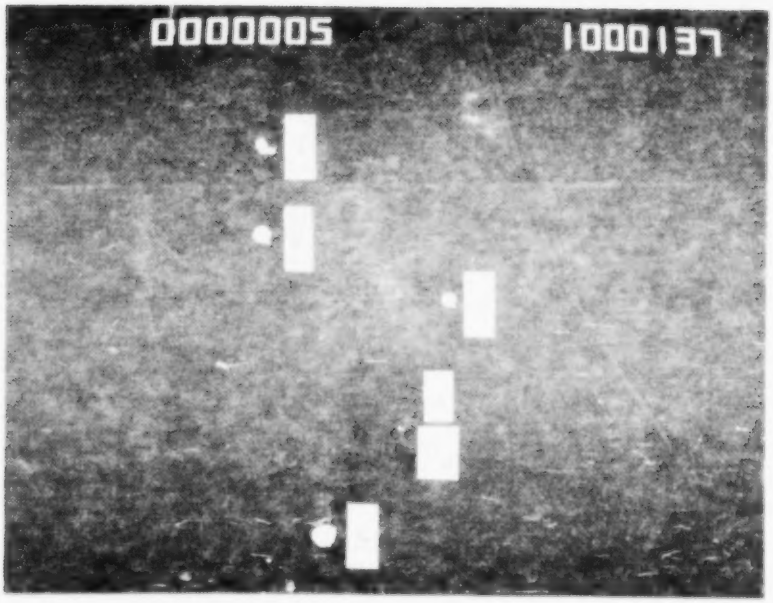

Figure 8. Definition of image parameters.

No. of Features Processed

Last Programmed Process (1) Performed and the Measured Value (93)




(a) z = 5 cm




(b) z = 7 cm

Figure 9. Same two planes shown in Figure 7 with all information below a preset threshold rejected.

When we changed the focus position to that leading to Figure 9(b), the following printout resulted.

TABLE 2. PRINTOUT OF INFORMATION FROM FIGURE 9(B)

| | X | Y | AREA | PERI | FH | FV | FE | FW | PH | PV | A/P | $A/P^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. | 283 | 162 | 315 | 53 | 13 | 14 | 16 | 16 | 16 | 16 | 5.943 | 0.112 |
| 2. | 286 | 275 | 310 | 64 | 20 | 20 | 24 | 24 | 20 | 20 | 4.844 | 0.076 |
| 3. | 521 | 353 | 227 | 55 | 18 | 16 | 22 | 22 | 16 | 18 | 4.127 | 0.075 |
| 4. | 456 | 516 | 11 | 13 | 4 | 3 | 8 | 4 | 3 | 4 | 0.846 | 0.065 |
| 5. | 366 | 674 | 596 | 92 | 28 | 26 | 34 | 30 | 26 | 30 | 6.478 | 0.070 |

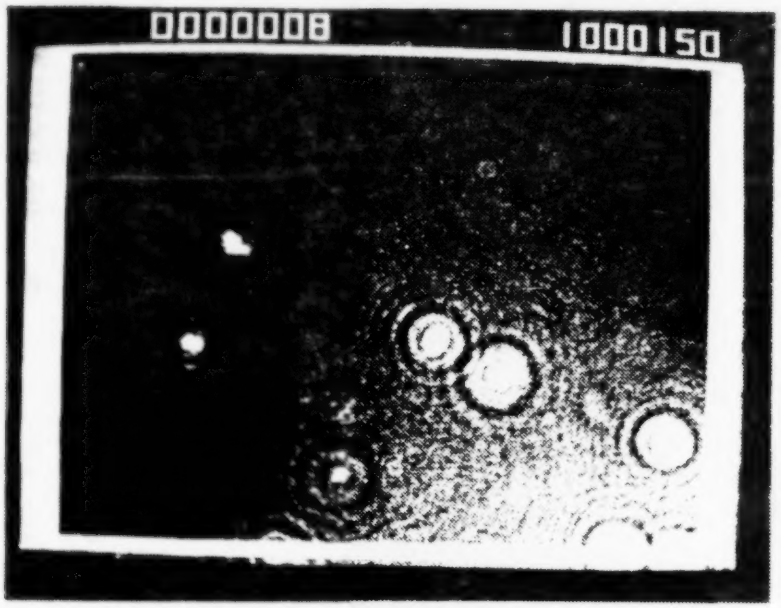
Comparing the data in Tables 1 and 2, the first two particles are the same. The particle diameters measured vary by 15 percent and 25 percent in horizontal feret respectively. The nearness in equality of vertical and horizontal feret are characteristic of spheres. The third particle is the same in both figures and so are the measured parameters to within a few percent. The fourth particle is different in the two figures and size is the reason. The fourth particle image in Figure 9(a) is small and did not carry enough intensity into the camera to be above the threshold in the setting for Figure 9(b) where it was considerably out of focus. The same is true for particle No. 4 in Figure 9(b) and No. 5 in Figure 9(a). The sixth particle in Figure 9(a) is the same as No. 5 in Figure 9(b). This is the largest particle in the set. Its size is determined within 7 percent the same for the two cases. In the actual setup the true focus position of these images could be easily seen to within better than one millimeter, though it is not completely evident in the photographs.

The key to successful implementation of such a system in holographic data reduction is its capability to handle noise. Figures 10 and 11 illustrate some of the studies in noise characteristics and system response. Several kinds of problems are illustrated here; and one by one we discuss their removal by the system processing functions. In Figure 10 the intensity across the image varies. When this variation is severe, picture "shading" correction capability can compensate for this effect. We did not find this necessary on data we were analyzing.

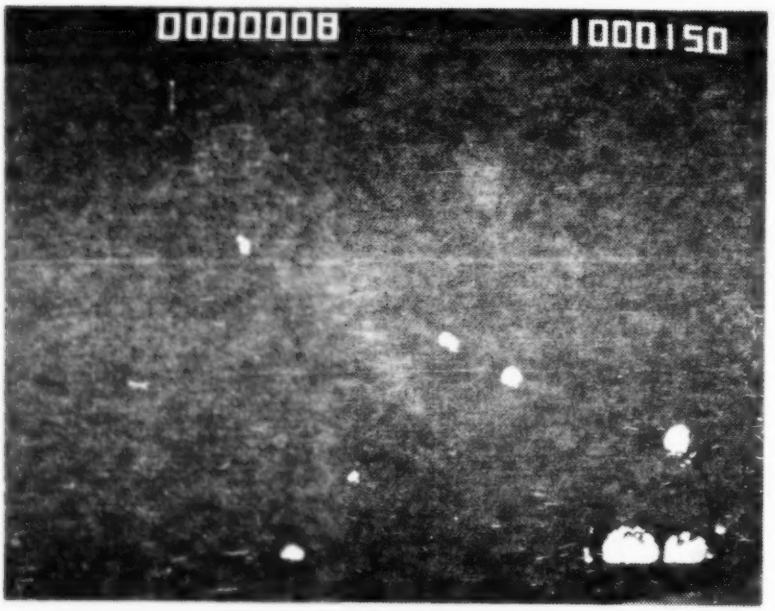
Speckle noise is normally a serious factor in image processing. We found in every case examined that speckle noise could be almost entirely rejected by the proper setting of a so-called resolution limit. Speckle noise is made up of intensity distributions of extremely small "points" of light. When the speckle size is much smaller than particles of interest, it can be rejected by existing instrument functions (compare Figure 10(a) and 10(b)).

The two images in the bottom right were circled by diffraction rings, even after processing. Again this effect is caused by the brighter image on the righthand side of the screen and can be removed by shading correction.

We studied the focusing problem and the possible system functions which can be used to drive an automatic scanning system to focus. We found several

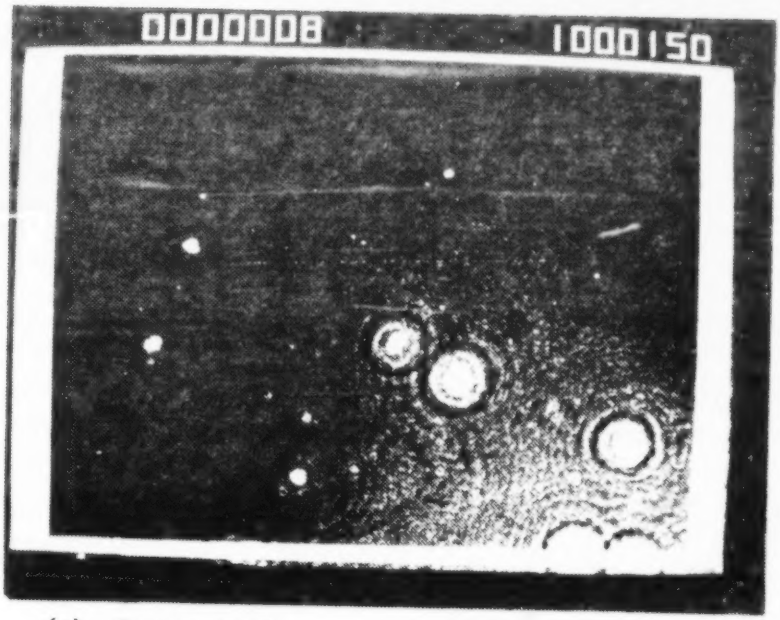



(a) Entire unprocessed image as presented to the image analyzer.

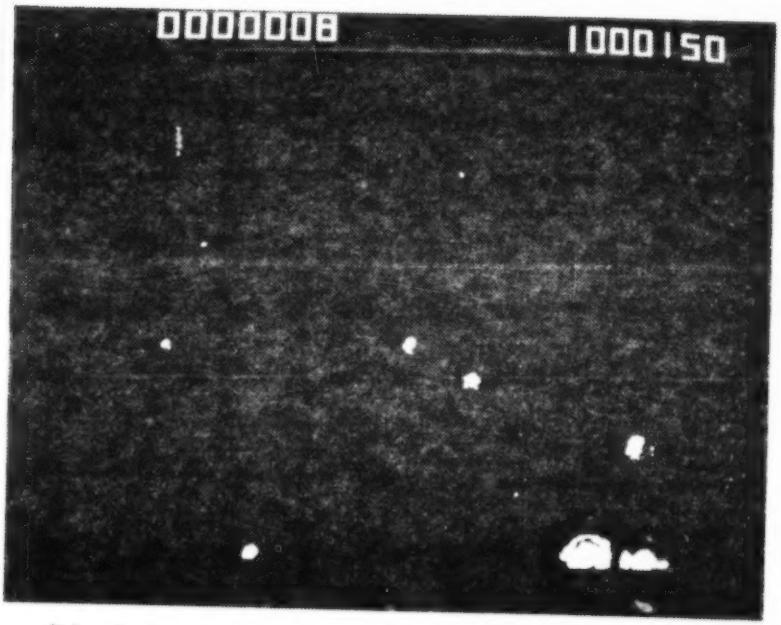



(b) Image after rejecting all information below a preset threshold.

Figure 10. One plane of the reconstructed three-dimensional image of a dust particle field.




(a) Unprocessed.




(b) Information above a preset threshold.

Figure 11. Two centimeter change in focus position of the image field shown in Figure 10.

ways to achieve this, but one in particular was rather simple and existed in the normal system programs.

Figure 12 shows recordings at two different reconstructed image planes. The system was set to examine that part of the image which lies between two intensity levels. The result is shown in Figure 13. It can be seen that each image is now represented by an annulus of light. This annulus of light associated with the original images varies much more rapidly with z position and the properties varying are easier to quantize than the entire image.

Figure 14 includes some interesting comparisons at two z positions for several particles. The image marked $A_a$ is present as an annulus in Figure 14(a). In Figure 14(b) this image (marked $A_b$) is out of focus 2 cm. The intensity in the image reaches Level 1 but not Level 2. Therefore, it is shown as a solid image. The image marked $B_a$ is closer to focus in Figure 14(a) than it is in Figure 14(b). The thickness of the annulus, therefore, increases in Figure 14(b).

Tables 3 and 4 are the printout data for these two cases.

TABLE 3. DATA FOR FIGURE 14(A)

| | X | Y | AREA | PERI | FH | FV | FE | FW | PH | PV | A/P | $A/P^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. | 379 | 80 | 17 | 22 | 5 | 4 | 8 | 8 | 6 | 7 | 0.773 | 0.035 |
| 2. | 253 | 160 | 26 | 52 | 10 | 9 | 14 | 14 | 17 | 17 | 0.500 | 0.010 |
| 3. | 254 | 274 | 70 | 86 | 15 | 16 | 18 | 18 | 27 | 28 | 0.814 | 0.009 |
| 4. | 492 | 347 | 17 | 31 | 9 | 10 | 6 | 12 | 10 | 10 | 0.548 | 0.018 |
| 5. | 489 | 353 | 11 | 23 | 10 | 16 | 12 | 16 | 5 | 9 | 0.478 | 0.021 |
| 6. | 118 | 375 | 23 | 29 | 6 | 6 | 8 | 8 | 8 | 9 | 0.793 | 0.027 |
| 7. | 675 | 460 | 12 | 26 | 6 | 5 | 8 | 6 | 7 | 10 | 0.462 | 0.018 |
| 8. | 691 | 518 | 7 | 4 | 1 | 2 | 2 | 2 | 2 | 1 | 1.750 | 0.438 |
| 9. | 338 | 637 | 18 | 21 | 7 | 3 | 8 | 6 | 4 | 8 | 0.857 | 0.041 |
| 10. | 324 | 639 | 30 | 24 | 9 | 6 | 12 | 8 | 5 | 9 | 1.250 | 0.052 |
| 11. | 343 | 640 | 8 | 12 | 5 | 2 | 4 | 4 | 2 | 5 | 0.667 | 0.056 |
| 12. | 351 | 645 | 1 | 4 | 1 | 1 | 2 | 2 | 1 | 1 | 0.250 | 0.063 |
| 13. | 356 | 656 | 22 | 23 | 5 | 8 | 10 | 10 | 8 | 6 | 0.957 | 0.042 |
| 14. | 305 | 662 | 8 | 12 | 4 | 2 | 4 | 4 | 2 | 4 | 0.667 | 0.056 |
| 15. | 316 | 663 | 28 | 47 | 12 | 17 | 20 | 8 | 17 | 13 | 0.596 | 0.013 |
| 16. | 356 | 663 | 17 | 16 | 4 | 15 | 10 | 16 | 6 | 4 | 1.063 | 0.066 |
| 17. | 308 | 671 | 20 | 22 | 5 | 7 | 6 | 10 | 7 | 7 | 0.909 | 0.041 |
| 18. | 354 | 671 | 26 | 21 | 6 | 7 | 10 | 8 | 7 | 6 | 1.238 | 0.059 |
| 19. | 331 | 674 | 120 | 172 | 27 | 29 | 32 | 26 | 36 | 42 | 0.698 | 0.004 |

The third particle in Table 3 is the first in Table 4. We will describe each measured parameter in more detail in a more appropriate figure later. However, these figures show other important points. In Table 3, 19 features (particles) are described. Starting with particle No. 9 through 19, all particles are very close to the same x-y position (i.e., around x = 320, y = 650). These are all, in fact, describing the region marked $C_a$. The

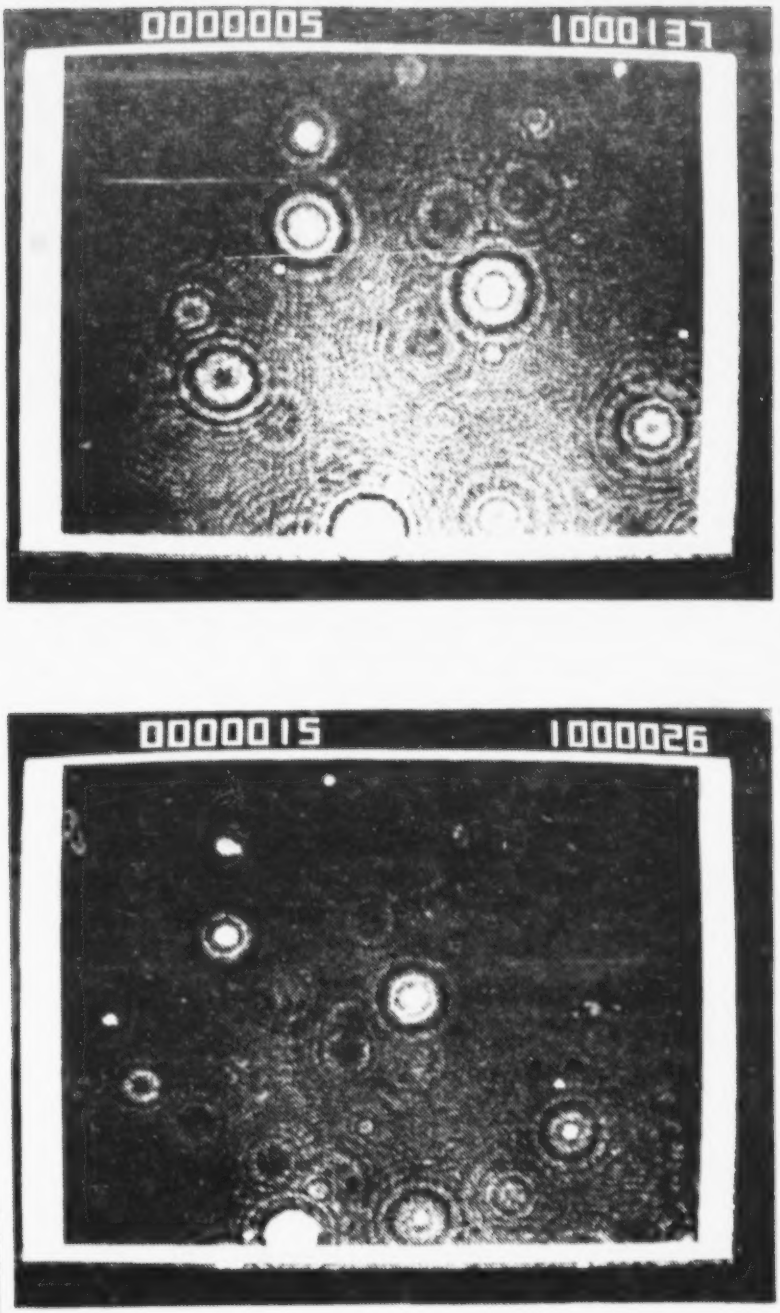
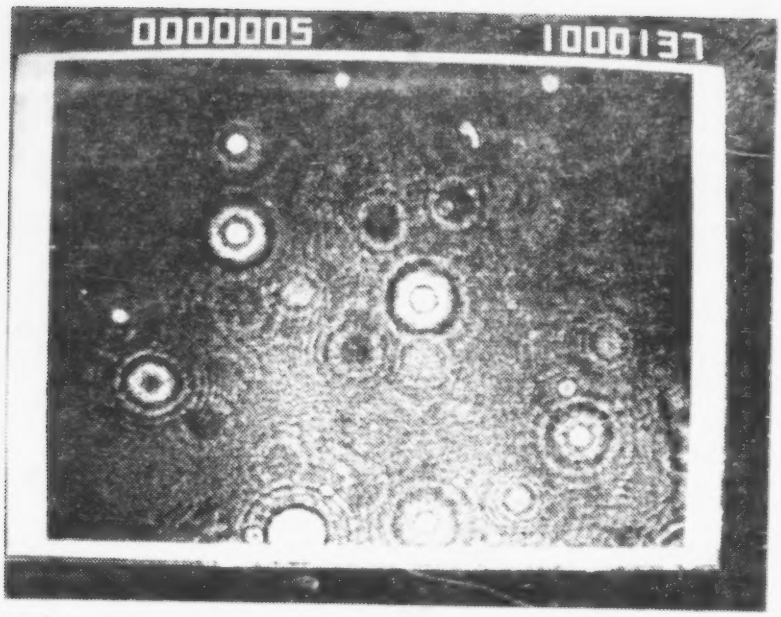
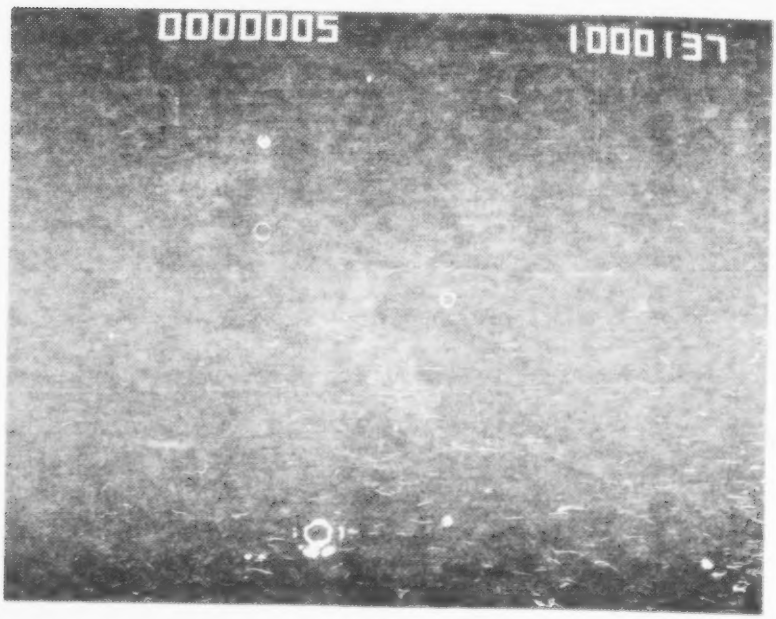



Figure 12. Two field different focus planes in the droplet.

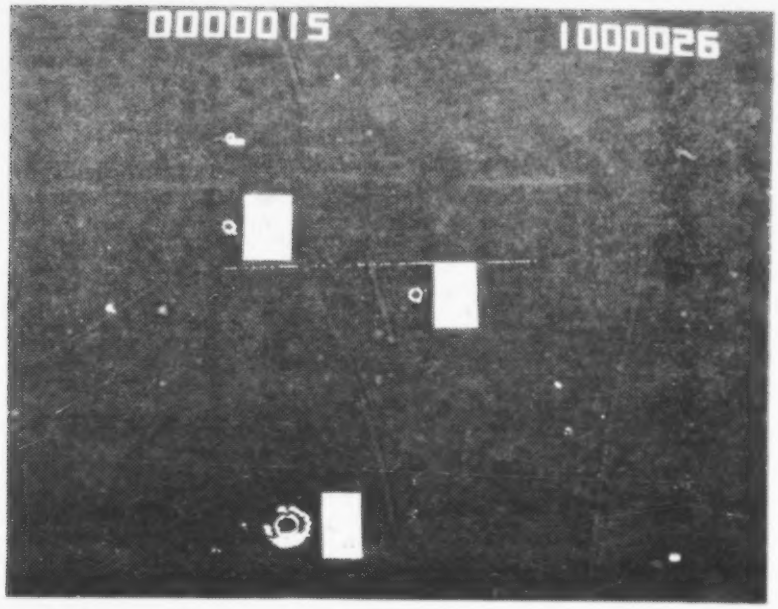



(a) Unprocessed image presented to the image analyzer.

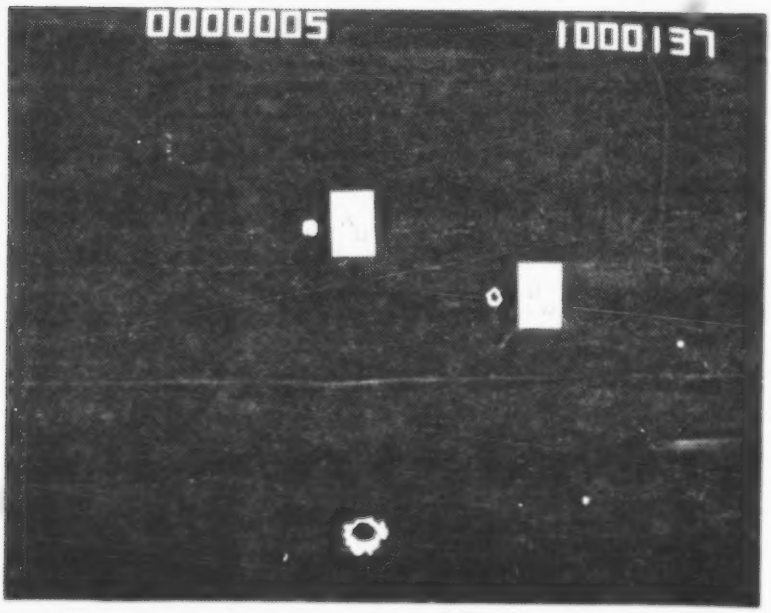



(b) Only intensity lying between two gray levels is displayed and processed.

Figure 13. Fog droplet field reconstruction.




(a) z = 0




(b) z = 2 cm

Figure 14. Scanning in focus while processing with two level detection.

large diffraction ring had broken into what was interpreted as particles. This "erroneous" result was deliberately left in this picture for purposes of illustration.

TABLE 4. DATA FOR FIGURE 14(B)

| | X | Y | AREA | PERI | FH | FV | FE | FW | PH | PV | A/P | $A/P^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. | 356 | 274 | 137 | 73 | 17 | 18 | 22 | 22 | 22 | 25 | 1.877 | 0.026 |
| 2. | 594 | 356 | 122 | 113 | 19 | 21 | 24 | 24 | 37 | 37 | 1.080 | 0.010 |
| 3. | 839 | 401 | 18 | 28 | 6 | 5 | 10 | 8 | 7 | 10 | 0.643 | 0.023 |
| 4. | 722 | 618 | 22 | 35 | 6 | 8 | 10 | 10 | 13 | 11 | 0.629 | 0.018 |
| 5. | 440 | 646 | 4 | 10 | 4 | 1 | 4 | 4 | 1 | 4 | 0.400 | 0.040 |

The diffraction ring can be rejected by the several methods mentioned, or it can be removed by the operator using a light pen. Any area on the screen which appears objectionable by an operator can be circled and removed entirely from the processed data. In Table 4 this particular region was moved outside of the detected area and rejected.

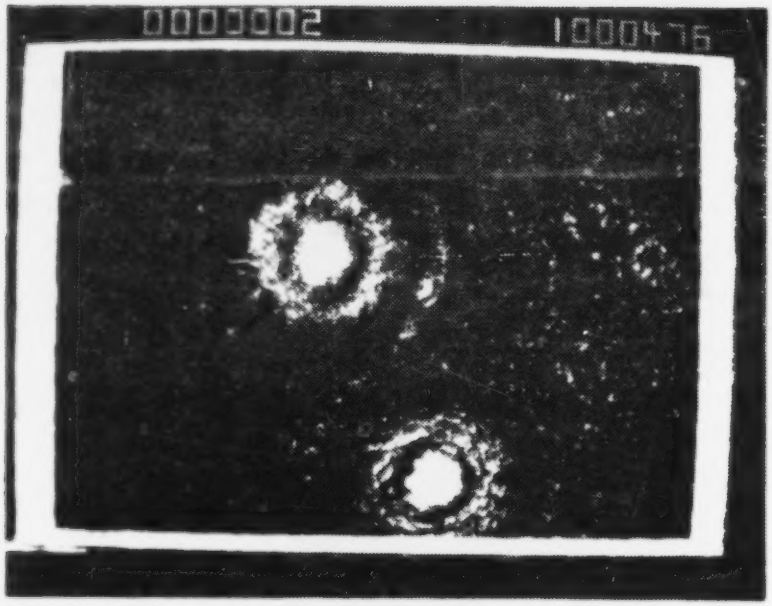
Figures 15 and 16 illustrate in more detail the properties of an image when passing through focus. We picked two reconstructed images of dust particles and magnified them to show more detail. They lie in close vicinity in x and y, but are considerably separated in z (about 1 cm). Figure 15 shows the unprocessed images. The particle size was about 30 microns. The top particle is in focus in Figure 15(a) while the bottom is in focus in Figure 15(b).

Figure 16 illustrates the system output when the two intensity levels are set and detection limited to between the levels. Comparing Figures 15 and 16 clearly shows how much better the focus position can be found when the annulus is displayed instead of the entire image. This is related to the fact that the gradient of the intensity at the image edge is what is used by an observer in finding focus. The thickness of the annulus is a direct measure of the intensity gradient at the image edge and, therefore, provides the operator more direct information. In the usual case, an operator must look at the intensity at the image edge and mentally determine changes in gradient. This can be done only if the image is being scanned, a reason why it is hard to illustrate in a report.

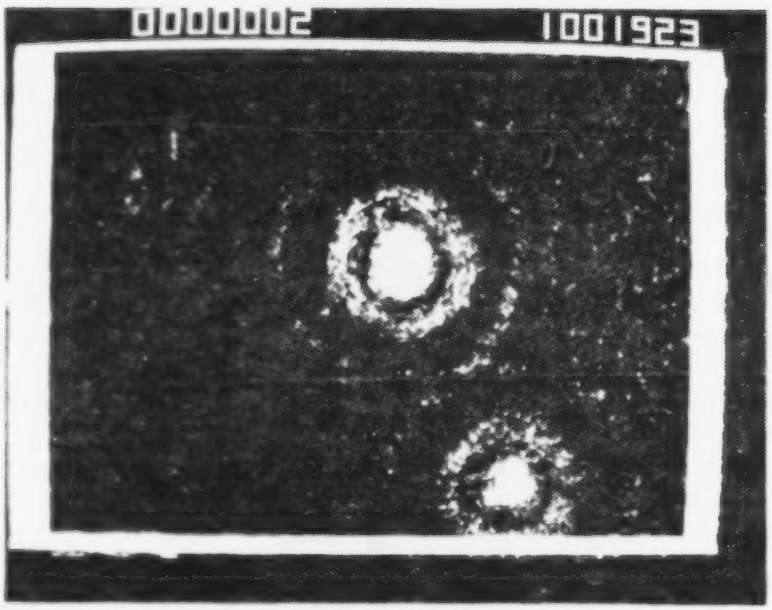
Tables 5 and 6 describe the processed images in Figure 16.

TABLE 5. DATA ASSOCIATED WITH FIGURE 16(A)

| | X | Y | AREA | PERI | FH | FV | FE | FW | PH | PV | A/P | $A/P^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. | 386 | 330 | 487 | 455 | 57 | 70 | 72 | 66 | 150 | 152 | 1.070 | 0.002 |
| 2. | 549 | 621 | 1142 | 397 | 56 | 60 | 60 | 64 | 109 | 133 | 2.877 | 0.007 |

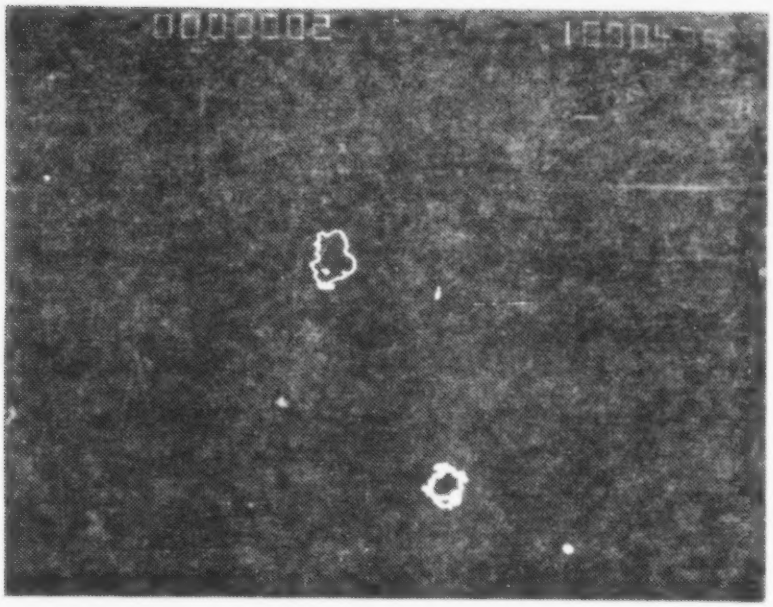



(a) Top particle in focus.

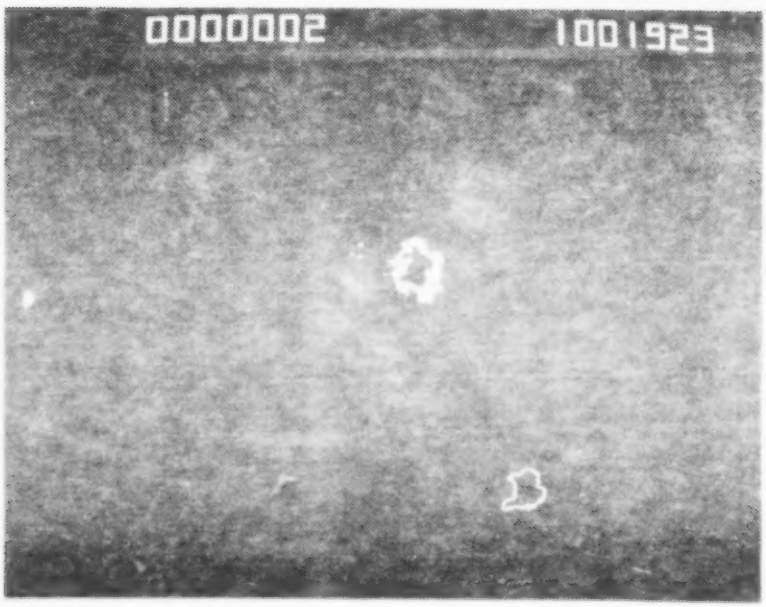



(b) Bottom particle in focus.

Figure 15. Two focus positions of a pair of 30 micrometer particles in a dust cloud.



(a) Top particle in focus.




(b) Bottom particle in focus.

Figure 16. Same particles as displayed in Figure 15 but shown here with two level detection.

TABLE 6. DATA ASSOCIATED WITH FIGURE 16(B)

| | X | Y | AREA | PERI | FH | FV | FE | FW | PH | PV | A/P | $A/P^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. | 494 | 349 | 1476 | 644 | 72 | 101 | 78 | 82 | 121 | 220 | 2.292 | 0.003 |
| 2. | 623 | 629 | 421 | 420 | 58 | 56 | 70 | 58 | 119 | 144 | 1.002 | 0.002 |

Here we describe in detail the signficance of the measured parameters.

x,y Positions--

The intensity distribution (particle image) numbered as 1 and 2 corresponds to the same particle in both figures. The x and y positions would be identical if the z-scan was precisely normal to the TV vidicon. Since it was not, the positions on the screen vary somewhat (more in x than in y).

Area--

The area of the annulus was thought to be a direct measure of in-focus position. We found this partially so, but we did observe cases where area actually gets smaller outside of focus. This is a property of the diffracted light field of the particle.

Perimeter--

Perimeter, like area, can get smaller outside of focus, especially for a non-spherical particle with complex edge detail. Particle No. 2 is an example.

Horizontal, Vertical, 45°, 135° Feret--

These are the same for a spherical particle. As shown here, they describe quite well the particle shape.

Ratio of Area to Perimeter--

We found this ratio to be an excellent guide to determine focus position. Recalling that the dimensions are in picture points, this ratio would equal unity when the annulus is two picture points wide because the area is equal to the number of picture points in the annulus times one, while the perimeter is equal to the number of picture points. Notice that A/P = 1.070 in Figure 16(a) and 2.292 in Figure 16(b) for the top particle. In Figure 16(a) the ratio A/P = 2.877 for the bottom particle while A/P = 1.002 in Figure 16(b). Through a number of studies we concluded that this ratio is an excellent parameter for finding focus.

The most logical approach appears to be to program the calculator to search for minimum A/P and to record the data at that value of x position of a traverse.

## SAMPLE DATA FROM HOLOGRAMS

The primary objective of this study was to determine feasibility for automating data reduction. Most of the effort was directed to the understanding of the properties of an individual image. In the ultimate application, a primary interest is in the overall particle field; namely, statistical samples, distributions and descriptions of the overall field.

While this study was in progress, a large number of holograms of particle fields were produced, not only in support of this project but also in support of three other projects, the task of which was to provide diagnostics of particle fields. One of the projects involved the use of holography to analyze fuel dispersions in explosive clouds. The third involved a study of combustion of fuel particles.

In this section we present sample data from those projects to illustrate the ultimate capabilities of holography in this type of study as well as to illustrate current limitations. In one of these studies six holograms of a fuel droplet cloud were analyzed in great detail. Many hours were spent in manual analysis, counting and sizing thousands of particles and studying their distribution in space. In the other holograms the study was limited to a statistical count.

Commonly a hologram contains the images of thousands of particles, more than enough for a statistical sample. The number of counts required to obtain a representative sample depends upon (1) the type of distribution, (2) the accuracy of each measurement, (3) the required accuracy of the distribution and the mean, and (4) a priori knowledge about the particle field. Although a detailed discussion of the statistics of particle measurement is beyond the scope of this report, a few approximate relations assist with the discussion here.

Consider a Gaussian distribution in diameter (a log normal distribution would perhaps be more true to nature). If, for example, we desire to determine the mean diameter we must make n measurements. Then our mean diameter $\bar{D}$ has a 68 percent chance of lying within $\pm S_m$ of the true value, 95 percent chance within $\pm 2S_m$ where $S_m$, the "standard error of the mean," is approximately

$$S_m = \frac{S}{(n-1)^{1/2}} \qquad (2)$$

and S is the standard deviation of the n measurements about the mean.

If, for example, we examine a particle field with a Gaussian distribution of $\bar{D}$ = 25 microns, and a standard deviation of 10 microns, the probability is 68 percent that error of the mean will be less than $\pm$ 10 percent if 17 measurements are made to compute the mean. To improve the probability to the 95 percent level requires 65 measurements. In actuality, the required number of measurements to be made can only be determined after enough measurements have been made to allow reasonable estimates of S.

In a given recorded volume, it is normally not necessary to analyze the entire volume. Only enough counts to provide an accurate representative sample are required. And this can be determined through statistics similar to that described above. In each z-scan, a known volume is swept through providing a total number and size distribution for that volume. This produces a number density. A second z-scan produces another set of data like

the first. The number of scans required can again be determined after a few scans are made by applying the above equation.

The xy positions are normally picked so that a significant space separates the volumes and no chance for overlap exists. However, when number densities are very low, it is advantageous to count every single particle in the hologram. In fact, more than one hologram could be required in the extreme.

Figure 17(a)-(c) illustrates representative particle size distributions taken from holograms produced in this study. Figure 17(a) was taken from a sample of nominal 30 micron diameter glass beads. A comparative count made with a microscope is shown with this case. Figure 17(b) is the analysis of an aerosol generator, while Figure 17(c) is the combined analysis of three holograms made on a windy day in the Mojave Desert.

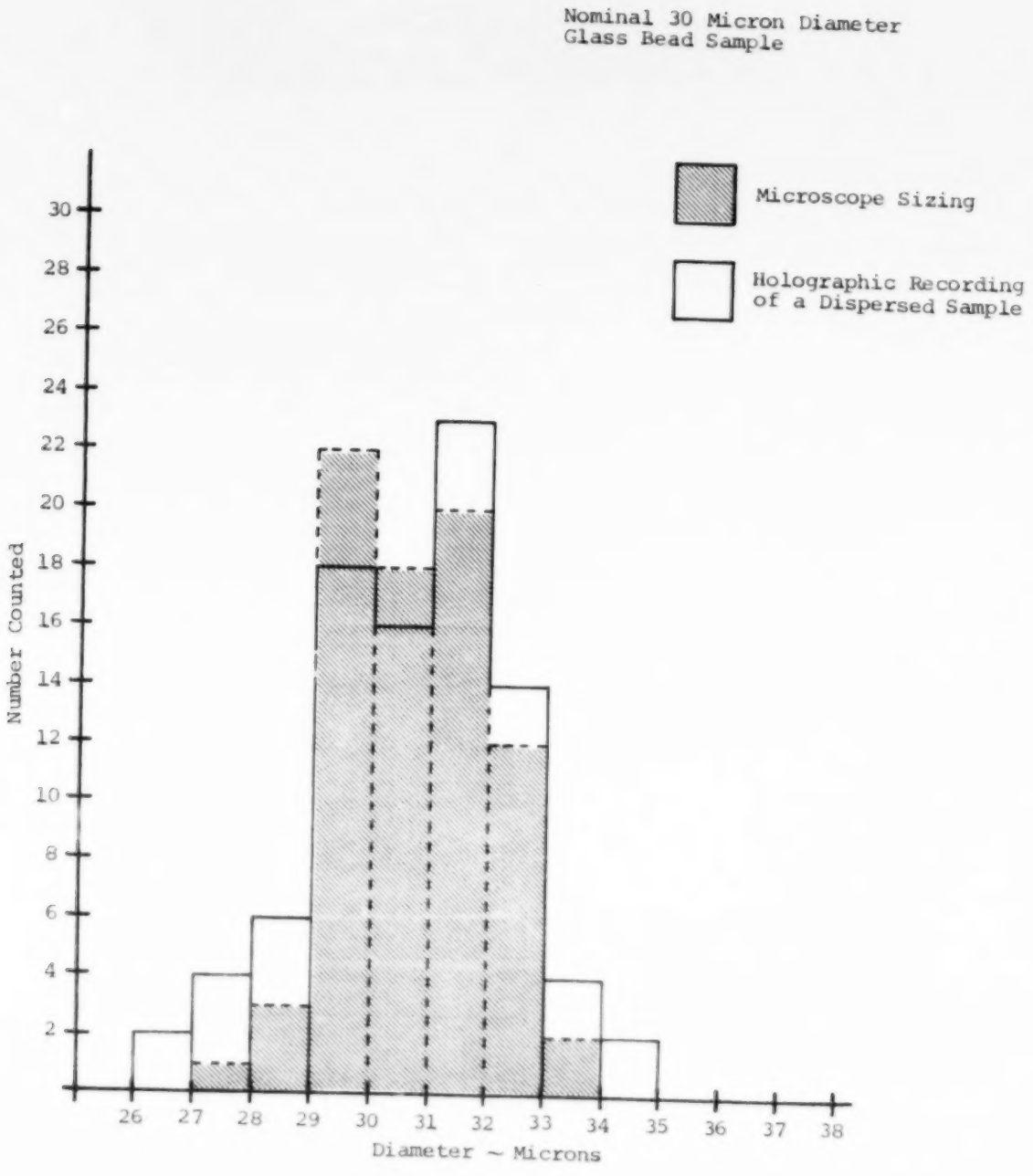



Figure 17(a). Holographic size analysis - glass beads.

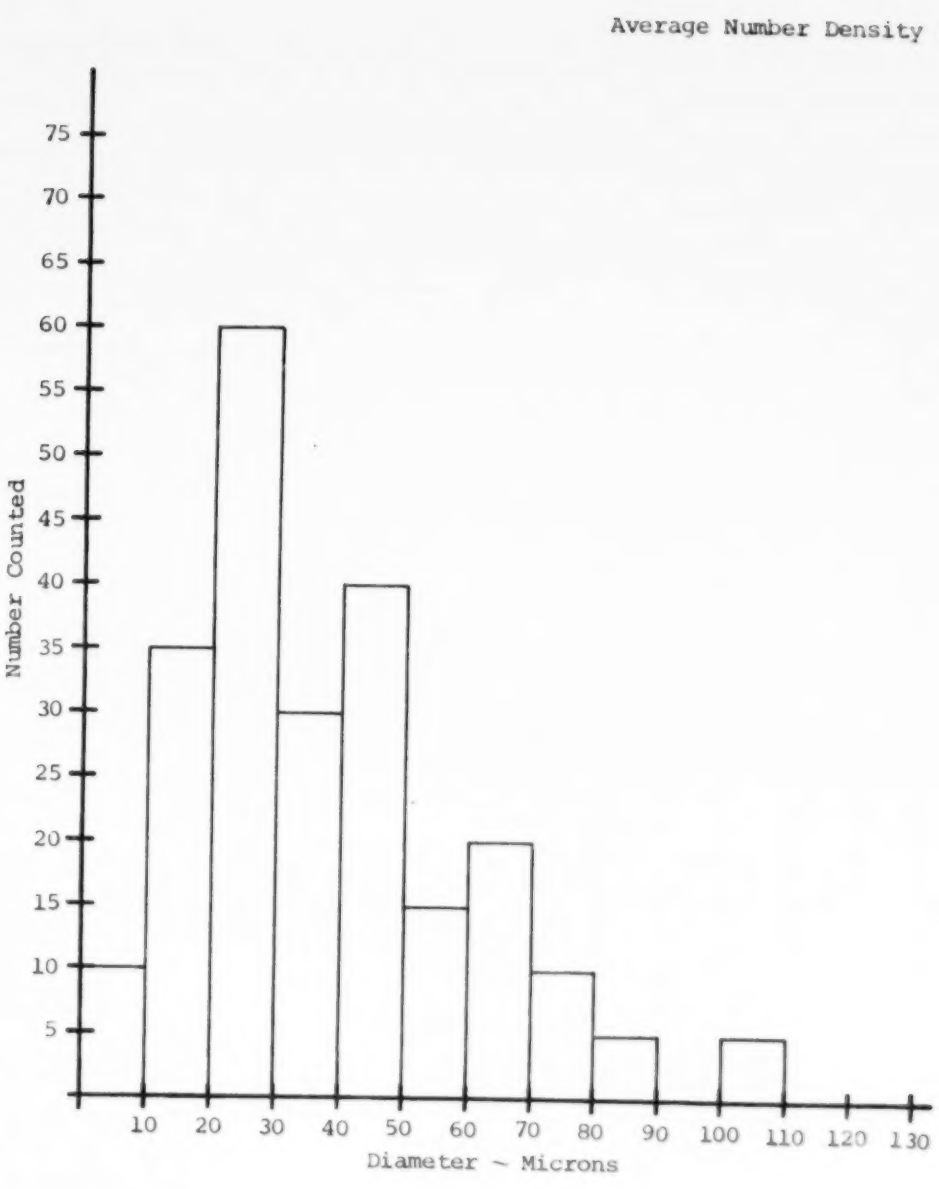



Figure 17(b). Holographic size analysis - aerosol spray.

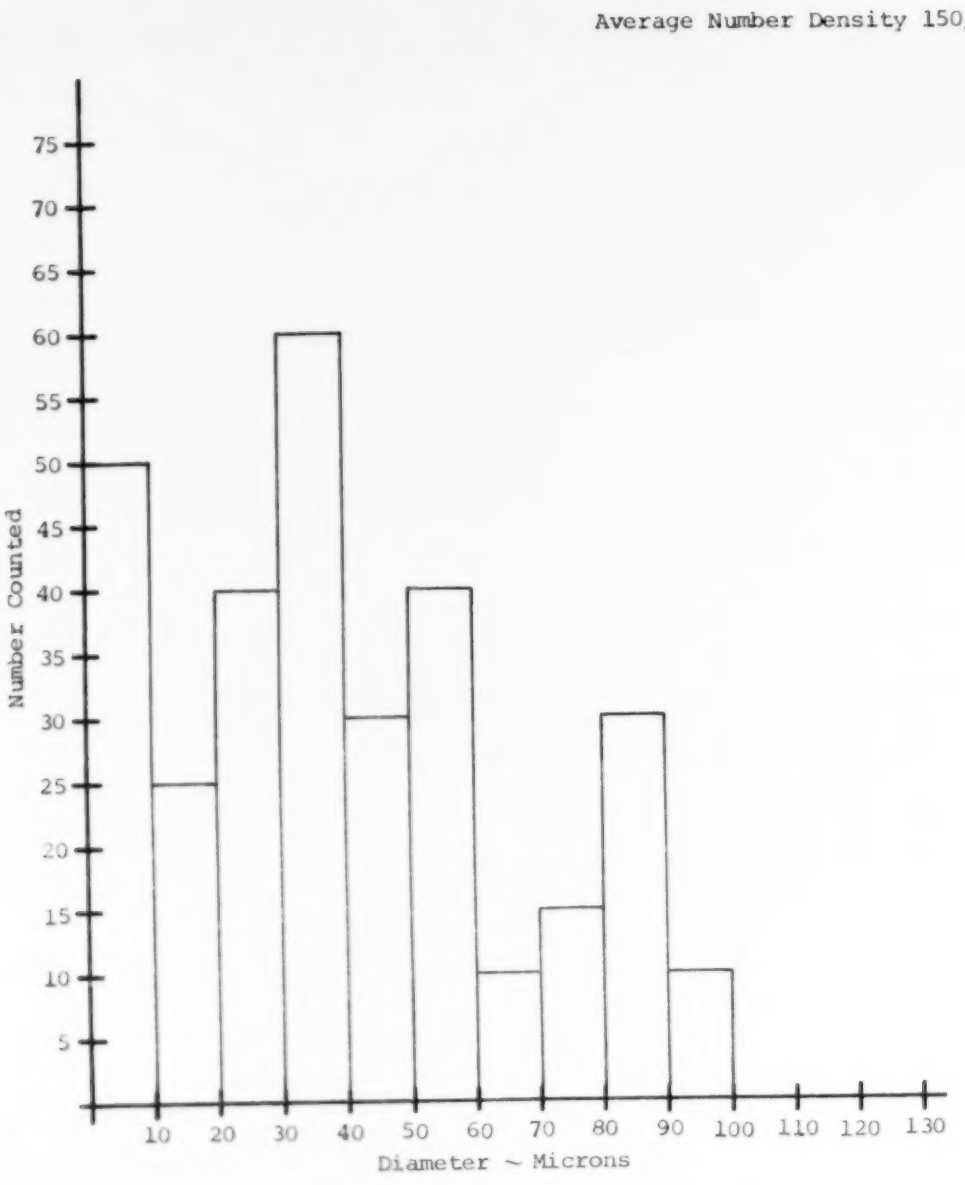



Figure 17(c). Holographic size analysis - dust storm.

## SECTION 5

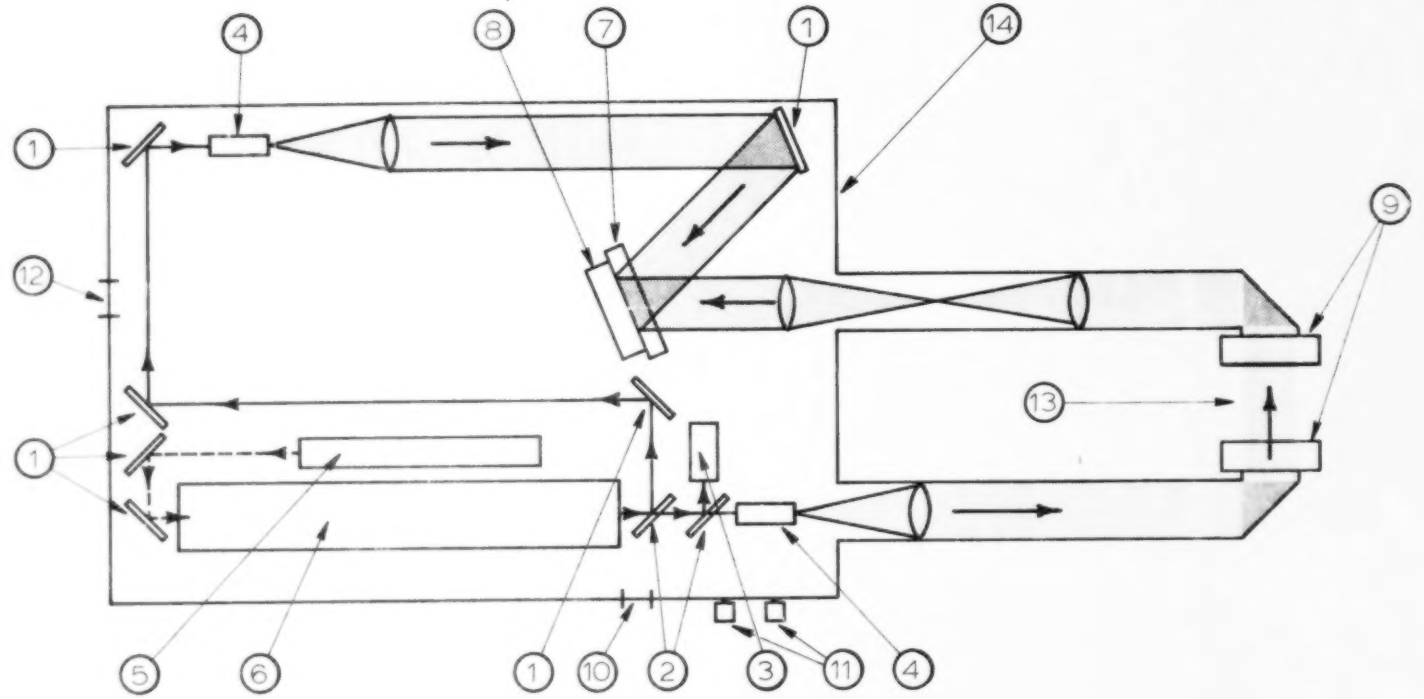
## THE SDL FIELD-PORTABLE PARTICLE HOLOCAMERA

SDL has developed and has refined during the past three years a field-portable particle holocamera for in situ diagnostics of particle fields in the size range from a few microns up to hundreds of microns in diameter. This system has undergone a wide variety of field tests during which time its refinement and modification to simplify its operation and to improve its reliability have continued. Figure 18(a)-(c) shows the system and a field installation. The heart of the system is a pulsed ruby laser which delivers a single or double pulse of light having a time duration of approximately 15 nanoseconds and a total energy output to about 100 millijoules. In the double-pulse mode, two such pulses can be produced with time separations ranging from a few microseconds up to approximately one millisecond. A helium-neon laser is built into this unit and passes precisely along the line of the ruby laser beam for the purposes of alignment and alignment check. The ruby laser beam is approximately two millimeters in diameter when passing from the laser. The first element it hits is the beam splitter which splits off a portion of the light to serve as a reference wave. The remaining portion of light passes through the beam splitter to a second beam splitter where a small portion is taken from the laser beam for the purposes of power output measurement. After this, the remaining light beam passes into a beam expander whereupon it is expanded to a two-inch diameter collimating lens which collimates the light and passes it out through a probe to a 90° turning mirror whereupon the laser beam passes through a shuttering system across the sample volume.

The purpose of the shutter system is primarily to keep the optics clean. We have tried many methods to keep the optics free of dust and contamination and we can find no method better than keeping the optics covered except for a fraction of a second during which the laser pulse exists. The laser is controlled to fire when the two protective shutters, labeled 9 in Figure 18(a), are in their full open position. The sample volume is approximately two inches by six inches deep. After the beam passes through the sample volume, the scattered and transmitted light are turned 90° by a turning mirror back into the collection system.

The collection system consists of an image transferring lens system which transfers the image of the sample volume back to a position near where the hologram is made.

The reference beam passes from the beam splitter just after the ruby laser to a system of mirrors after which it is beam expanded and collimated and then turned to mix with the object wave at the hologram.




1. Mirror
2. Beamsplitter
3. Detector
4. Beam Expander/Spatial Filter
5. Alignment Laser (HeNe)
6. Ruby Laser
7. Film Plane Shutter
8. Film/Plate Holder
9. Shutter
10. Port for Auto Collimator
11. External Laser Alignment
12. Viewing Port
13. Sample Volume
14. Purged/Protective Housing

Figure 18(a). Field-portable particle holocamera.

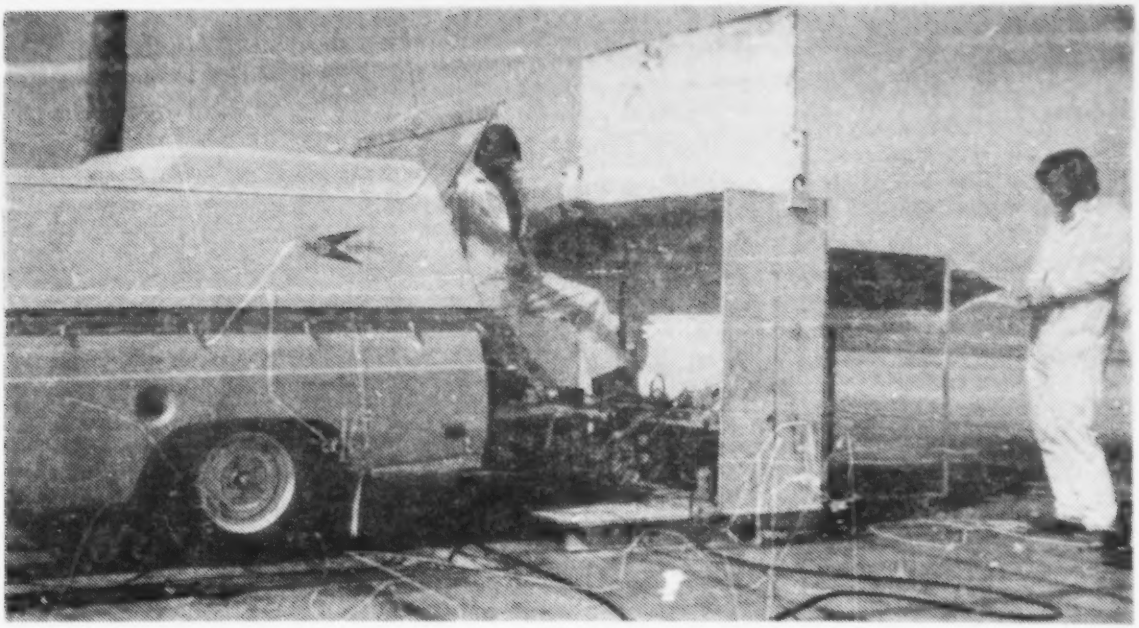


Figure 18(b). Side view of the holocamera installed behind a shield as applied in explosion diagnostics.

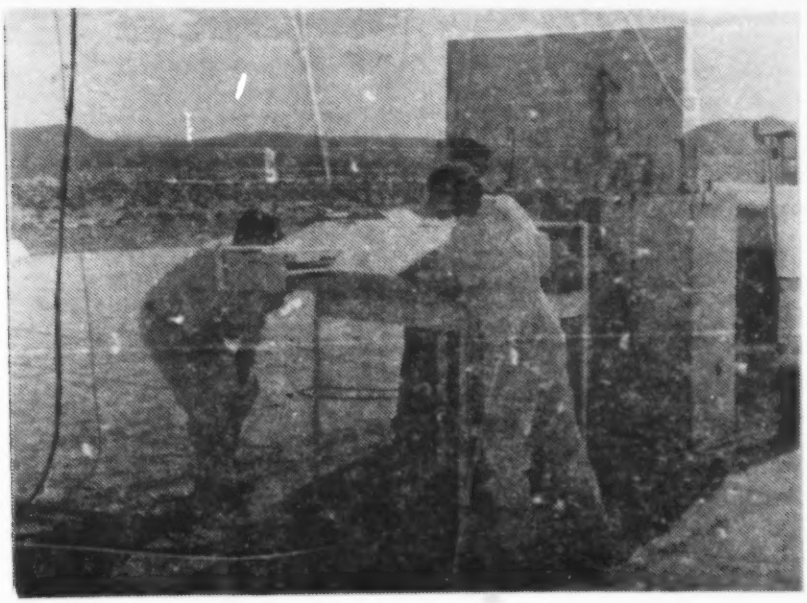


Figure 18(c). Front view of the shielded optics package.

With this system, either in-line holography or off-axis holography is possible. Simply removing the reference wave converts this to an in-line holocamera. We have found in a number of cases that holograms made in this system with the reference waves can be used in either mode, in-line or off-axis, and sometimes there are advantages to being able to do both.

The basic configuration of this holocamera is not especially novel. Nevertheless, a number of design features built into this system were found important in its utility in a field-type environment. The entire system is housed in an aluminum sealed box. The box is purged with dry nitrogen to keep contamination outside. A cover lifts off for access to the inside. A small hatch allows access to the film plane for exchanging photographic plates. The entire optical system inside the rectangular portion of the box is mounted on a secondary reinforced surface which is vibration isolated by a rubber mounting from the outside parts of the box. This allows a certain amount of torquing of the outside of the box without misaligning the internal optics.

The alignment of the ruby laser can be done without removing the cover of the system. This is done by inserting the optical alignment tool through the sides of the box and alignment adjustments to the ruby laser are extended by flexible cables to the external part of the box. The actual condition of alignment can be observed by peering through peep holes at the rear of the box to the frosted glass on the back of the hologram holder observing the reference wave and the object wave as produced with a helium-neon laser. As a final check, the ruby laser itself can be fired and the actual beams which will be making the hologram can be observed on the frosted glass at the back of the plate holder through this porthole labeled 12.

The packaged optical system weighs approximately 100 pounds. The power supply which controls and powers the ruby laser is in a separate container. It weighs approximately 200 pounds. This entire system fits in a small portable trailer which is used to transport the system to various places for our application.

We found that the holograms produced in this system in most naturally occurring environments were of sufficient quality to be reducible by the Quantimet image analyzer. This is not to say, of course, that the problem of automatic data reduction is completely solved. A considerable amount of work is left in automating the features which we have described which are necessary to make the image analyzer perform the data reduction task.

The holograms which are described in the previous section which were ultimately used to perform the studies with the Quantimet system were made in this system with the reference beam removed. We were not able within the scope of this study to do a similar analysis for the off-axis case.

## SECTION 6

## A PROPOSED AUTOMATIC HOLOGRAPHY DATA REDUCTION SYSTEM

Based upon these results, we are now in a position to design an automatic holography data reduction system. The purpose of this section is to present such a conceptual design based on the use of the Quantimet 720 image analyzer currently in operation at the EPA facility. We will assume that the holograms for which this system is designed are at least of the quality of those tested during this program.

Figure 19 is a schematic layout of a suggested reconstruction system, while Figure 20 is a schematic layout of the electronic and control system. The hologram would be mounted in a computer controlled xyz traverse. It would be illuminated by a collimated helium-neon laser, and the reconstructed image would then be reimaged and magnified onto the TV camera. Therefore, the proper positioning of the hologram in its x, y, and z dimensions would place the three-dimensional image onto the vidicon surface. At any instant the image analyzer can be addressed to provide the information describing the intensity distribution on the surface of the TV screen. At any one instant this information includes those parameters which were mentioned in Section 4 for images for both in focus and out of focus and, to a certain extent, noise on the TV camera. For any one given set of holograms of a particular quality an operator must intervene at the beginning to adjust the image analyzer such that its adjustment falls within the optimum operating range dependent upon the quality of the reconstructed image. Such adjustment could, in fact, be computer controlled; although we believe at this stage computer control of everything in this process is not necessary nor desirable. We feel that a certain amount of operator judgment will always be necessary in this data reduction just as it is in almost any type of data reduction of field data.

The operator initially sets the thresholds on the TV screen such that a given threshold is well above the noise level and, at the same time, considerably below the level of intensity of the smallest particles which are desired to be analyzed. This defines the particle and the display concerning the x-y position of the particle. At this point, sizes of those particles which are in focus or nearly in focus would normally be printed out as data. A third dimension, however, must be located to insure that only particles in focus are analyzed and retained as data.

As has been described, this can be accomplished in a number of ways with existing data outputs from the Quantimet 720. The experiments performed here suggest that the two-level detection method would be a principal method in performing this task. The computer which drives the hologram in its xyz

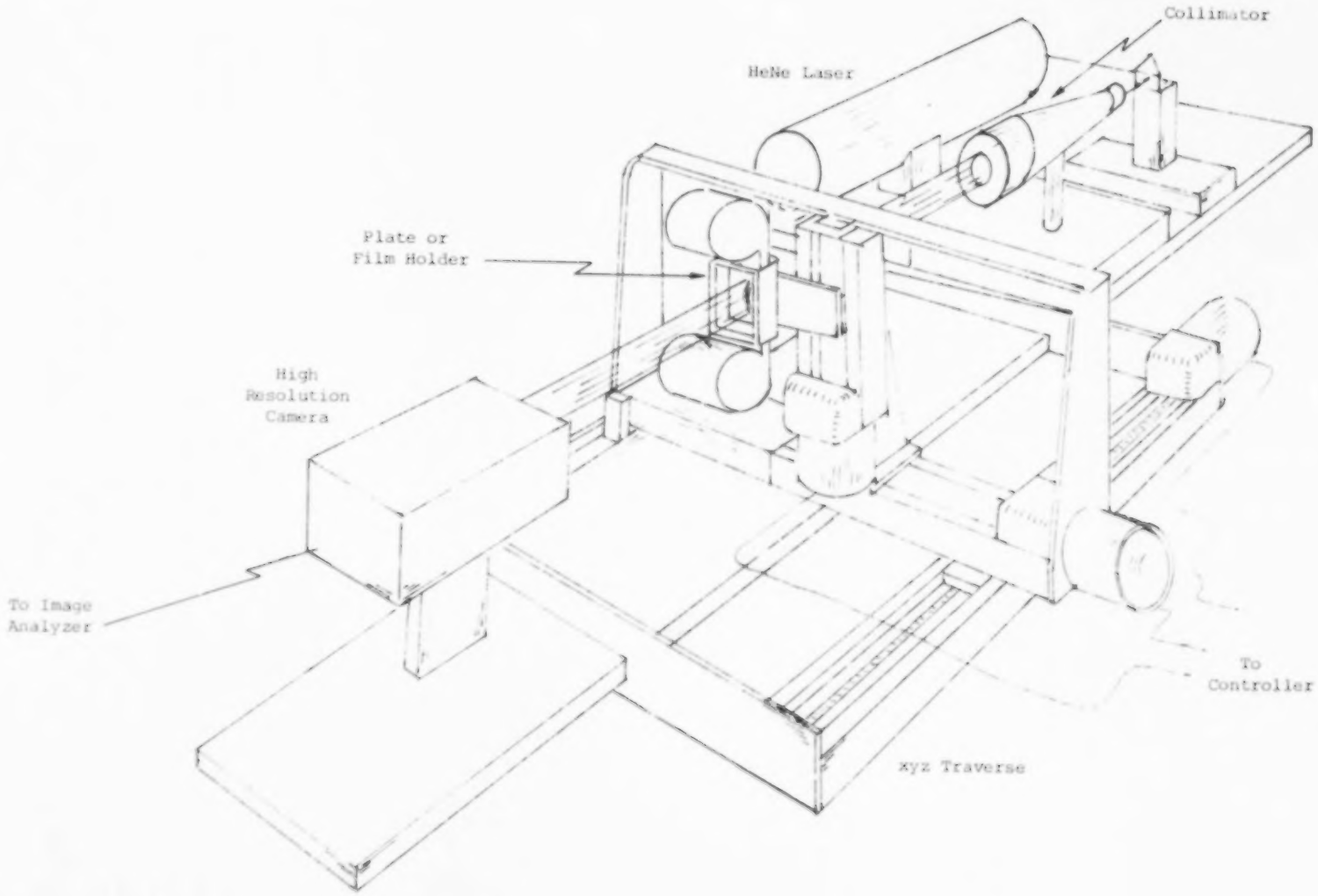



Figure 19. Holocamera reconstruction system.

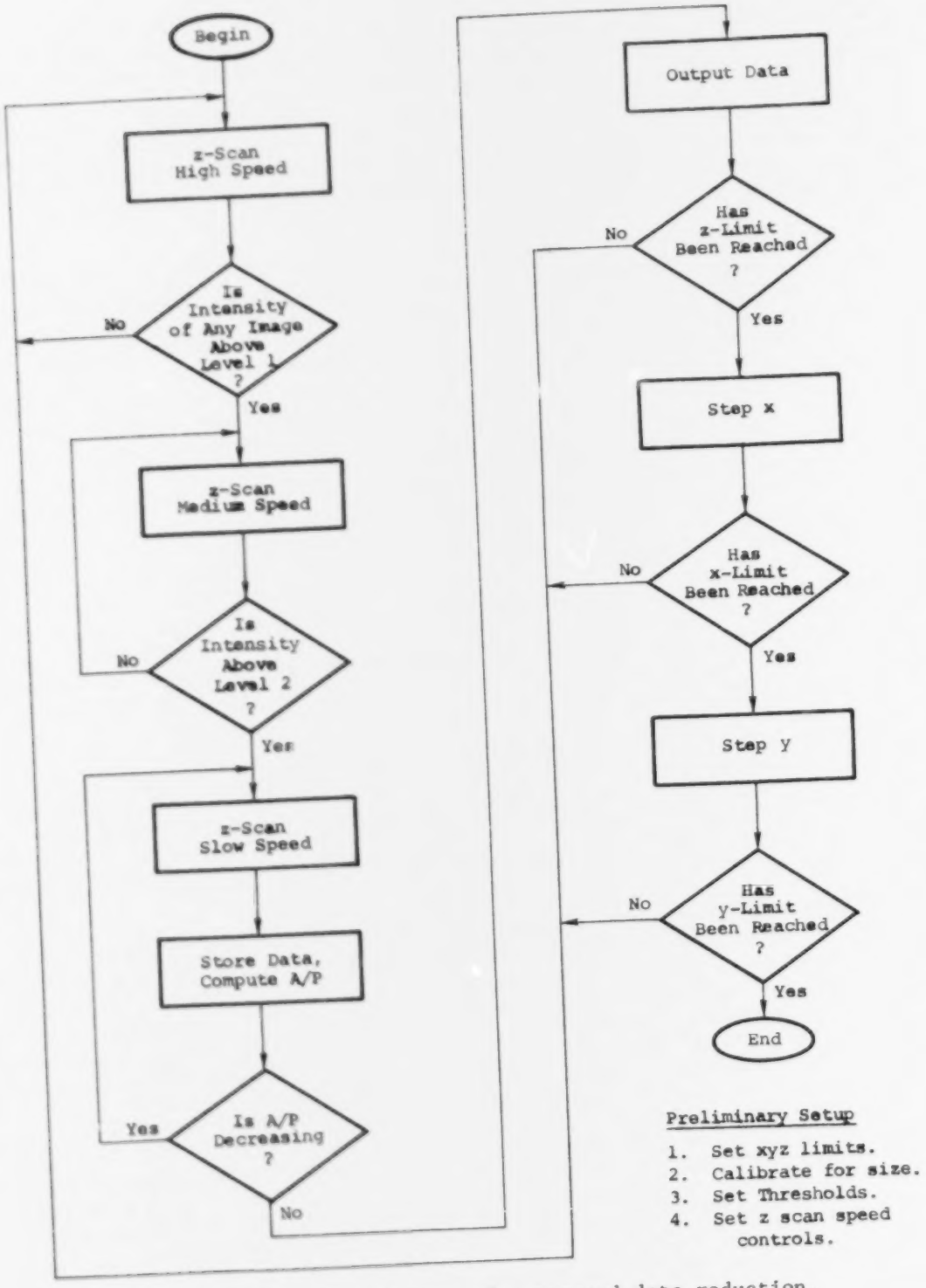



Figure 20. Flow diagram of automated data reduction.

position would be set to position the hologram at a given x-y coordinate and then start the translation in the z dimension. The annulus defined by the two levels of detection in this method would then be continuously analyzed in the computer with reference to its ratio of area to perimeter. When this ratio becomes minimum, the particle would be designated as an in-focus particle and the information describing that image at that time would be accepted as data. This would include its xyz positions, its particle dimensions, and the parameter area over perimeter.

The z scan of the hologram can be carried out at a fairly high rate until one reaches the proximity of a particle. When the holographic image is far removed from focus, no image intensity is detected on the TV screen, and at any such time the z scan can be run at a fairly high rate. When the first level of detection is surpassed by an intensity distribution, this is an indicator that a particle is approaching its focus. The scan speed could at that point be reduced. When the second level of threshold is surpassed by the intensity, the focus position is even more closely being reached. At this point, the computer-driven traverse could be slowed even further. The ratio of area over perimeter of this annulus would be continuously analyzed by the computer in search for a minimum. All data in this region of the scan would be stored in a buffer memory until the focus position has been determined. When the ratio of area over perimeter is minimized, that data associated with that position would be accepted as retained data and would be transferred to a recording disc or tape. The remaining data in the buffer memory could, at that point, be erased or simply renewed. Since the xyz position of all particles is recorded, the computer can be programmed not to accept two particles in the same xyz position such that an overlapping of the volume being scanned could be rejected.

When the end of the holographic volume was reached, the computer would drive the traverse in an x dimension until a new region on the hologram was examined once again in its z position. It appears that a hologram of the size which we are describing here could be reduced in this fashion in a matter of time ranging from a few minutes to one hour, depending upon how many particles were in the recording.

A number of other program operations should be included to correct for possible discrepancies, some of which have been described in Section 4. For example, when very large particles exist in a volume, the diffraction rings around these particles are often counted as particles. We have shown that one can reject this noise to some extent by setting resolution of the system to a value at approximately equal to the smallest particle of interest. Another method which we believe would be required in this study is to have a volume predetermined which would be designated as the smallest allowed volume to contain more than one particle. If such a volume was designated, then any such volume containing more than one particle would be rejected by the computer. We have found in these studies that noise is characterized typically by this kind of information. Where noise does exist in a reconstructed image, it appears as a number of particles clumped in a small volume.

The very reason for having performed this study has actually prevented us from getting certain statistical information which will be necessary to

refine such a system. One needs, after the construction of an automated holographic data reduction system, to perform analysis on statistical samples of holograms such that factors can be fine tuned on some statistical basis. Our conclusions so far have been strictly based on specific small number samples. The computer must be programmed to set certain limits on holographically reconstructed images which are based upon statistics derived from performing studies with the system itself. The initial setup of such an automated system would depend upon the quality of the hologram being reduced. However, it is reasonable to believe that a given set of holograms made under similar conditions would retain the same setting as that for the initial hologram. We know, however, this is true only to the extent that the particle field being diagnosed is similar. The ultimate noise in the reconstructed image is not only dependent upon the hologram quality, but it is also dependent upon the numbers and sizes and distributions of particles in the field of interest.

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